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Cryogenic Wind Tunnel Models

Design and Fabrication

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I

PREFACE

The Cryogenic Wind Tunnel Models Workshop was held May 5-9, 1982, at NASA Langley Research Center. The principal motivating factor for the workshop was the construction and approaching commissioning of the National Transonic Facility (NTF) at Langley. Since the NTF can achieve significantly higher Reynolds numbers at transonic speeds than other wind tunnels in the world, and will therefore occupy a unique position among ground test facilities, every effort is being made to ensure that model design and fabrication technology exists to allow researchers to take advantage of this high Reynolds number capability. Since a great deal of experience in designing and fabricating cryogenic wind tunnel models does not exist, and since the experience that does exist is scattered over a number of organizations, there is a need to bring existing experience in these areas together and share it among all interested parties. As a result, this workshop included representatives from government, the airframe industry, and universities.

The papers presented herein are grouped according to session. Each paper includes a short synopsis of the presentation, along with the visual aids used. A list of non-Langley attendees is included at the front of the document.

Grateful appreciation is expressed to the invited speakers and authors, who shared their experiences and views with the workshop participants. Thanks are also due to all those who contributed to many useful exchanges of information.

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OVERVIEW OF NATIONAL TRANSONIC FACILITY MODEL TECHNOLOGY PROGRAM

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INTRODUCTION

For several years, Langley has had a research program aimed at developing technology for cyrogenic model design and fabrication. The basic objectives of the program are (1) to investigate and develop the required technologies for design and fabrication of models and stings for use in the National Transonic Facility (NTF), (2) to integrate these technologies into the design and fabrication of two generic models and sting supports, designated Pathfinder I and II, and (3) to develop an initial model criteria document. The accomplish these objectives, tasks were undertaken both in house and out of house. The in-house tasks focused around the design and fabrication of models of a generic transport and a generic maneuvering aircraft configuration (Pathfinder I and II, respectively). A contractual study was initiated with the General Dynamics Corporation to address the design problems associated with maneuvering aircraft having thin wings and flow-through fuselage-mounted inlets. Two configurations, the F-16E and F-111 TACT, were selected to represent the problems associated with both single and twin engines. The areas of concentration are (1) flow-through engine simulation, (2) sting arrangement, (3) provision for both force and pressure data capability, and (4) definition of allowable test envelopes for both configurations.

AERODYNAMIC DESIGN CONSIDERATIONS

Surface Finish

To obtain the data accuracy desired for most high Reynolds number transonic tests, it is desirable to provide a model surface roughness that will not produce a measurable aerodynamic effect. Some of the potential areas influenced by surface roughness are skin friction, transition, shock wave location, and boundary layer separation. More information exists on the effects of roughness on skin friction than on the other three areas. The current criterion for admissible roughness height is the maximum surface roughness height that will not affect skin friction. The data in figure 1 show the variation of admissible roughness height k_a in a zero-pressure-gradient turbulent boundary layer with Reynolds number $R_{\bar{c}}$, where mean chord $\bar{c}$ is taken as 0.20 m (0.65 ft). This mean chord is representative of a transport model sized for the NTF. Shown on figure 1, for reference, are the maximum NTF Reynolds number, the Boeing 747 cruise Reynolds number, and the maximum Reynolds number for current tunnels. At a given Reynolds number, any roughness height falling below the admissible roughness curve in figure 1 will produce no skin friction penalty. The shaded band on figure 1 shows the range of typically specified and achievable surface finishes for current transonic models. The current specified model surface finishes appear to be compatible with a significant part of the NTF Reynolds number range. However, as is noted on figure 1, the admissible roughness curve is for a surface with uniformly distributed three-dimensional particles. The surface of a typical model does not resemble a uniform distributed particle roughness. Thus, an experimental program is planned at Langley to determine the equivalent distributed particle roughness for typical NTF model surfaces.

In order to carry out this experimental program, a good definition of the topography of a typical model surface is needed. The instrumentation that is almost universally used to measure model surface roughness in model shops is the stylus profilometer type equipment. There are at least two potential problems associated with the stylus profilometer: roughness slope too steep and roughness frequency too high. (It should be noted that the stylus radius is typically 2.5 µm (100 µin.).)

Since there are no published data to verify that the stylus profilometer accurately determines surface topography data on surfaces typical of high Reynolds number models, the National Bureau of Standards (NBS) compared the topography of a surface typical of NTF models as measured by a stylus profilometer and a stereo scanning electron microscope. In addition, the stylus profilometer has great difficulty measuring surface finishes on curved surfaces similar to the leading-edge region of wings. Because the boundary layer is thinnest in this region, the local skin friction is the most sensitive to surface roughness. Therefore, it is highly desirable to have the capability of measuring surface finish over the leading edge. Towards this end, the NBS is developing a light-scattering system to measure the surface finish accurately on surfaces with high curvature.

Orifice Criteria

As the Reynolds number increases and the boundary layer becomes thinner, its thickness can become small compared to the orifice diameter. Under these conditions, the orifice-induced pressure error may not be negligible. An additional orifice error, which may be significant in magnitude, can result from orifice imperfections. Although there are several types of orifice imperfections, experimental data exist only for a burr around the orifice. A burr can produce flow separation in the orifice, causing additional streamline deflection. Some other types of hole imperfection which can produce pressure error are out-of-round orifices, particles in the orifice, and not having the longitudinal axis of the orifice normal to the model surface, to mention the most common.

Figure 2 illustrates the effect of Reynolds number on orifice-induced pressure error. For reference, the maximum NTF Reynolds number, Boeing 747 cruise Reynolds number, and maximum Reynolds number available in current tunnels are shown. From these data, it may appear that a 0.13-mm-diameter (0.005 in.) orifice is satisfactory for the complete range of NTF Reynolds numbers since the maximum error is only 0.008. However, all the data in figure 2 are for relatively small values of d/δ^*, where d is orifice diameter and δ^* is boundary layer displacement thickness ($d/\delta^* = 4.0$). However, since d/δ^* for high Reynolds number conditions can be on the order of 100, erroneous conclusions might be drawn regarding the level of the orifice-induced pressure error if only these data are applied. Further, simply extrapolating the curves for the 0.51- and 0.25-mm-diameter orifices to the high Reynolds number region can lead to erroneous conclusions. Therefore, a test program is under way at Langley to extend the data shown in figure 2 to higher values of d/δ^* and higher Reynolds numbers.

Fabrication Tolerances

Model fabrication tolerance requirements are difficult to determine because of the accuracies necessary in experimental and analytical studies to define these tolerances at transonic speeds. Currently, transonic model tolerances are determined by past experience and by the accuracy of the machines used to fabricate the model. Since the tolerances affect data accuracy and model costs, it is desirable to develop improved techniques for tolerance definition.

STRUCTURAL DESIGN CONSIDERATIONS

Practical considerations of cost dictated a tunnel test section size (2.5 m maximum) such that cryogenic operation alone will not achieve the desired Reynolds number capability; therefore, the NTF is designed for combined cryogenic and high-pressure operation. As illustrated in figure 3, utilization of the higher stagnation pressures will require a more detailed approach to model design such that the model and model components can be designed to lower margins of safety. This will involve more detailed analysis from both static and dynamic loads considerations, better quality control during fabrication, and in some cases extensive static proof loading and on-line monitoring of loads and dynamic response. While it is generally believed that the high dynamic pressures will often produce as great a challenge to the model designer as the cryogenic temperatures because of material stress limits, the more subtle effects of cryogenic temperatures and the new problems that will undoubtedly be encountered with increased experience cannot be overemphasized.

Model Sizing

Size has a strong impact on the model design and fabrication problems, with the larger models generally being easier to fabricate. However, larger models result in increased tunnel wall interference effects, and it is this wall interference effect that determines the maximum acceptable model size for aerodynamic testing.

For a given airplane size, the higher the aspect ratio, the higher the tunnel dynamic pressure required for full-scale simulation, and thus the higher the design load. This is illustrated in figure 4. For a given wing area, an increase in wing aspect ratio is the result of increased wing span, as illustrated in the sketch at the right of the figure. When a wind tunnel model is sized on an absolute value of the wing span, the scale of the model must be reduced as the aspect ratio is increased. Therefore, to maintain full-scale Reynolds number, the model must be tested in the tunnel at a higher dynamic pressure. The main part of the figure illustrates this effect for three airplane sizes. The symbols indicate the model design or wind tunnel test dynamic pressure required to achieve full-scale Reynolds number for three typical aircraft sizes. The slope of the lines shows the increase in wind tunnel dynamic pressure required to maintain full-scale Reynolds number if the aspect ratio is increased on these configurations.

Test Envelopes

The operating envelope for a Mach number of 0.8, shown in figure 5, illustrates the dynamic pressure requirements for typical transport configurations. The range of Reynolds number with dynamic pressure for existing 2.0- to 2.5-m ambient-temperature tunnels is also shown for reference. For the Airbus A-300 size airplanes, full-scale Reynolds number can be obtained in the cryogenic case at a dynamic pressure of approximately 2000 lb/ft^2. This is roughly comparable to the maximum dynamic pressure capability in the Calspan tunnel with the injectors operating, and illustrates the large increase in Reynolds number due to reduced temperature, with model stresses no larger than are obtained in current tunnels. To match full-scale Reynolds number for transports the size of the Boeing 747, an additional 50-percent increase in dynamic pressure is required. The achievement of this test condition will require relaxation of the model design safety factors currently in use, which will be compensated for by a more detailed design analysis.

The Reynolds-number/dynamic-pressure envelope for the NTF at a Mach number of 0.9 is shown in figure 6, along with the Reynolds number requirements for a typical maneuvering fighter at altitudes from 3000 to 12,000 m. Although the required dynamic pressure varies greatly over this range, the model lift force and model stresses for simulation of a constant airplane load factor are nearly constant. This results from the fact that the temperature variation as a function of pressure (corresponding to condensation at a local Mach number of 1.4) results in a variation of Reynolds number with dynamic pressure between 10,000 and 40,000 ft that is essentially proportional to that of the airplane in the atmosphere. Therefore, the simulation of a constant load factor over this altitude range results in a constant model lift force, just as it will on the airplane. This is illustrated in figure 7. As Reynolds number is increased at the minimum NTF temperature, the tunnel dynamic pressure is required to increase. If a constant airplane dynamic pressure or load factor condition is simulated, however, the model angle of attack (and thus the lift coefficient) will be reduced, and the resulting $C_L q$, or lift, will be constant with the changing Reynolds number. If, for model design considerations, changes in wing span load distribution with changes in angle of attack are ignored, this constant lift load will result in the wing stress being approximately constant. Therefore, the stress limit will correspond to the maximum $C_L q$, which will impose a limit on the maximum airplane g's or load factor, that can be simulated at full-scale Reynolds number. This limit is independent of the magnitude of Reynolds number. Therefore, the dynamics of the model/sting/balance configuration, which is a function of dynamic pressure, or q, will govern the maximum Reynolds number at which full-scale conditions can be simulated.

The effect of the $C_L q$ limit is summarized in figure 8. The open symbols represent flight conditions at which, for a constant simulated load factor condition, the model load is constant. It is interesting to note that the strength requirements for a model tested in an existing tunnel (solid symbol) at a dynamic pressure of approximately 15,000 lb/m^2 and a lift coefficient corresponding to a given load factor at 40,000 ft altitude are identical to what they will be in the NTF at any of the full-scale conditions indicated by the open symbols for the same simulated load factor. This results from the fact that the increase in Reynolds number between the solid symbol and open circle corresponding to 40,000 ft altitude is due entirely to the benefit of cryogenic operation. The point of this discussion is that both model strength and model/balance/sting system dynamics will play an important role in determining maximum usable NTF test capability for a given configuration.

The structural design effort has focused on the problems and methods of analysis associated with the high working stresses, dynamic effects, and thermal considerations. Additionally, material requirements are being investigated from the standpoint of strength, fracture toughness, stability, and fillers.

CONCLUDING REMARKS

The purpose of this workshop is to provide a forum for exchanging information and ideas on the status of cryogenic wind tunnel model design activities at Langley and in industry. It is also hoped that we will be able to collectively assess the major concerns of the prospective users and discuss research and development activities needed to address these concerns.

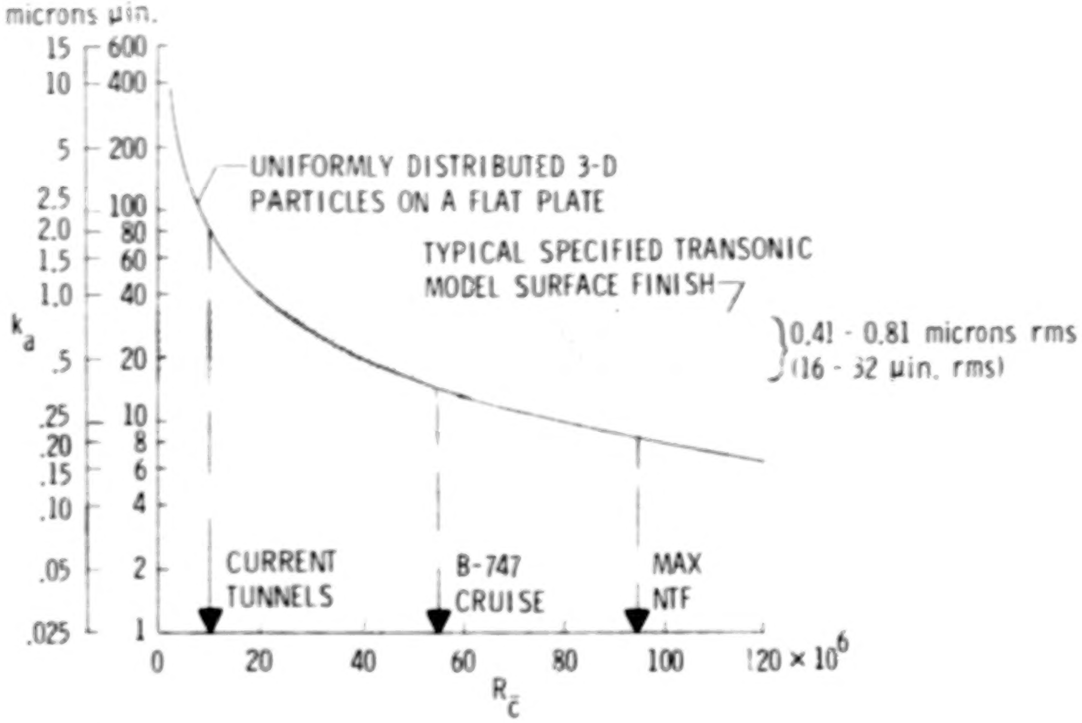

Figure 1.- Acceptable roughness for typical NTF model. $\bar{c}$ = 0.20 m.

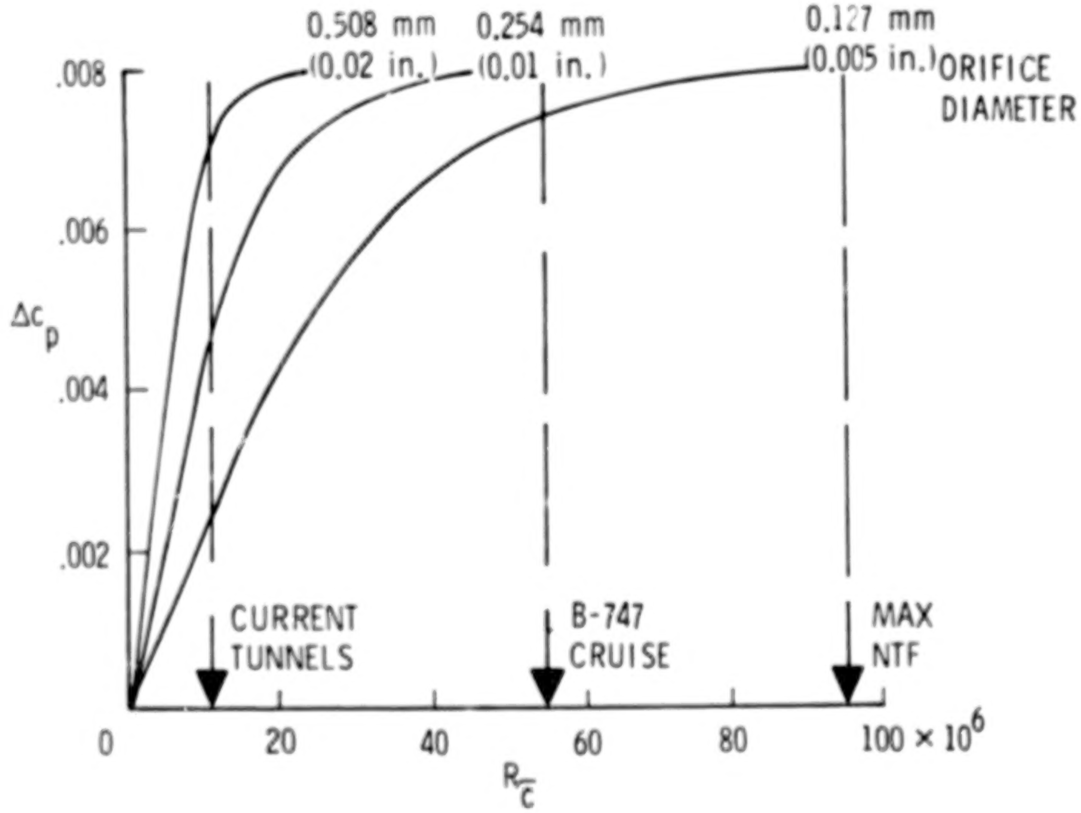

Figure 2.- Orifice-induced pressure error. Skin friction coefficient = 0.0022; $\bar{c}$ = 0.20 m.

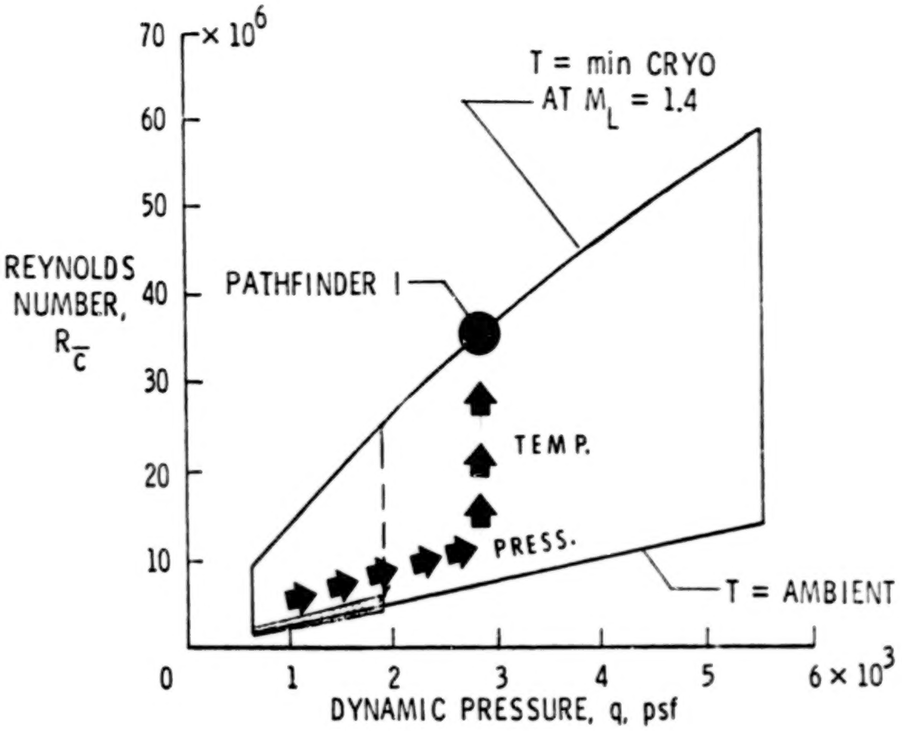

Figure 3.- NTF operating envelope at M = 0.8. $\bar{c}$ = 5.4 in.

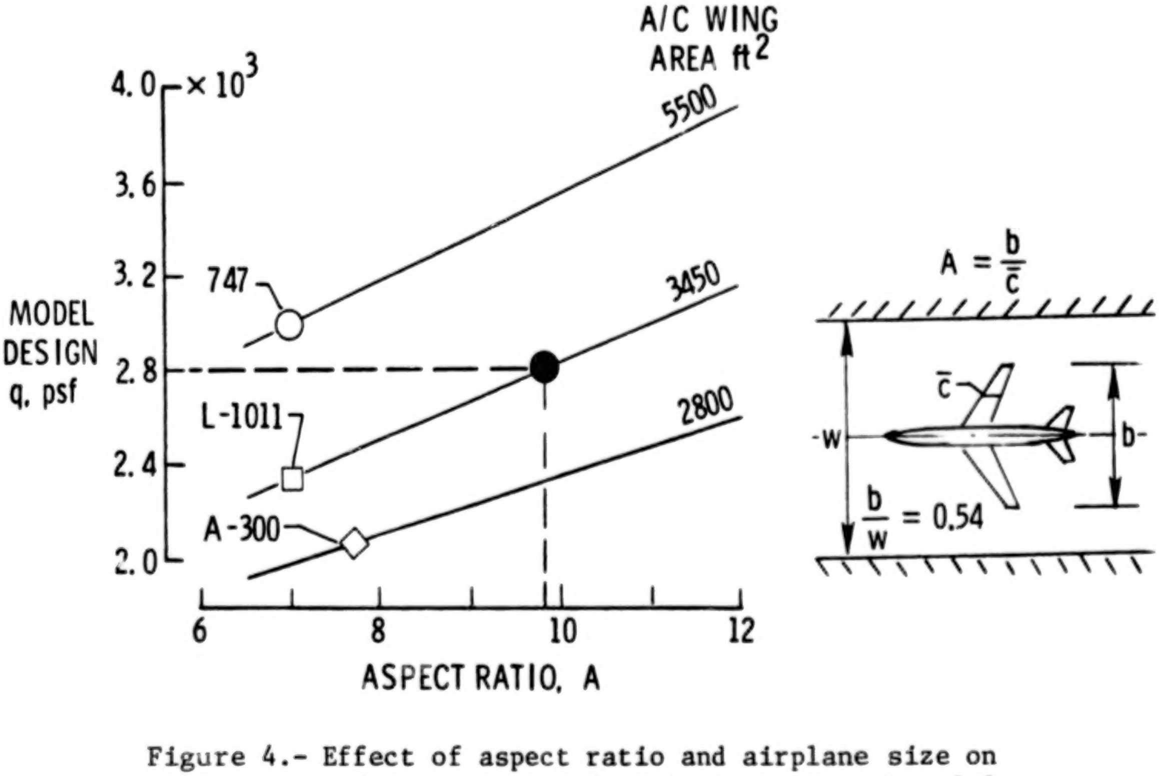

Figure 4.- Effect of aspect ratio and airplane size on model design q. R_c = full scale at M = 0.8; alt. = 35 000 ft; T = minimum.

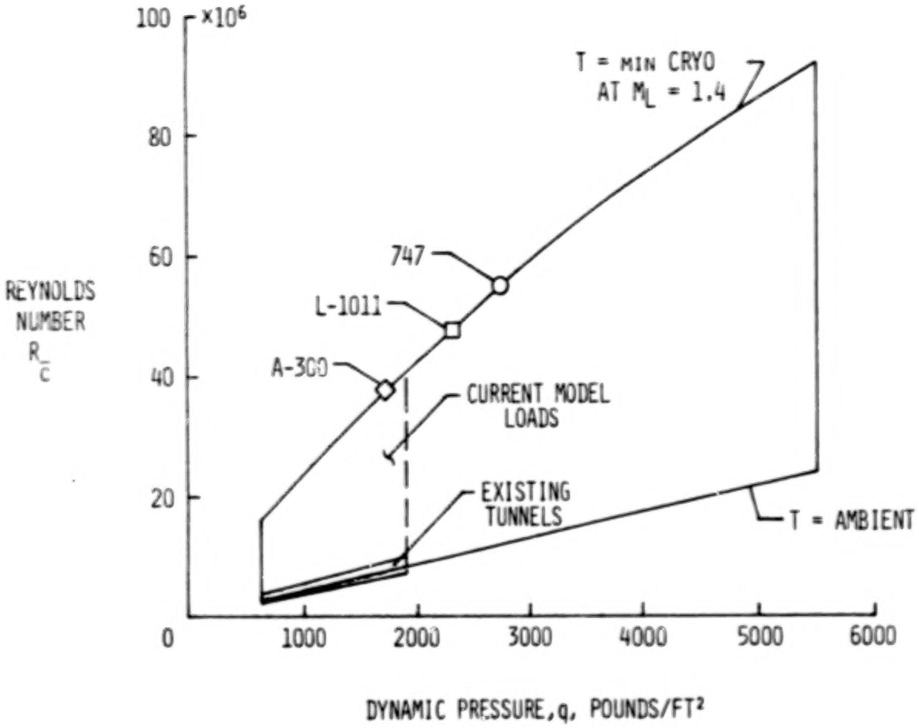

Figure 5.- NTF operating envelope at M = 0.8. Model span = 1.50 m.

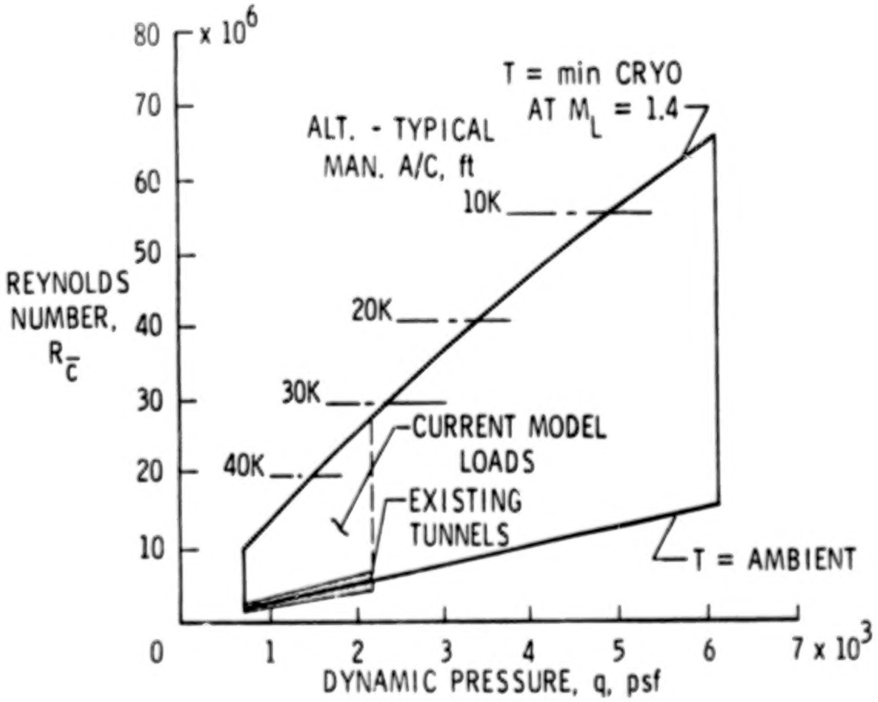

Figure 6.- NTF operating envelope at M = 0.90 for Pathfinder II. for Pathfinder II. $\bar{c}$ = 5.6 in.

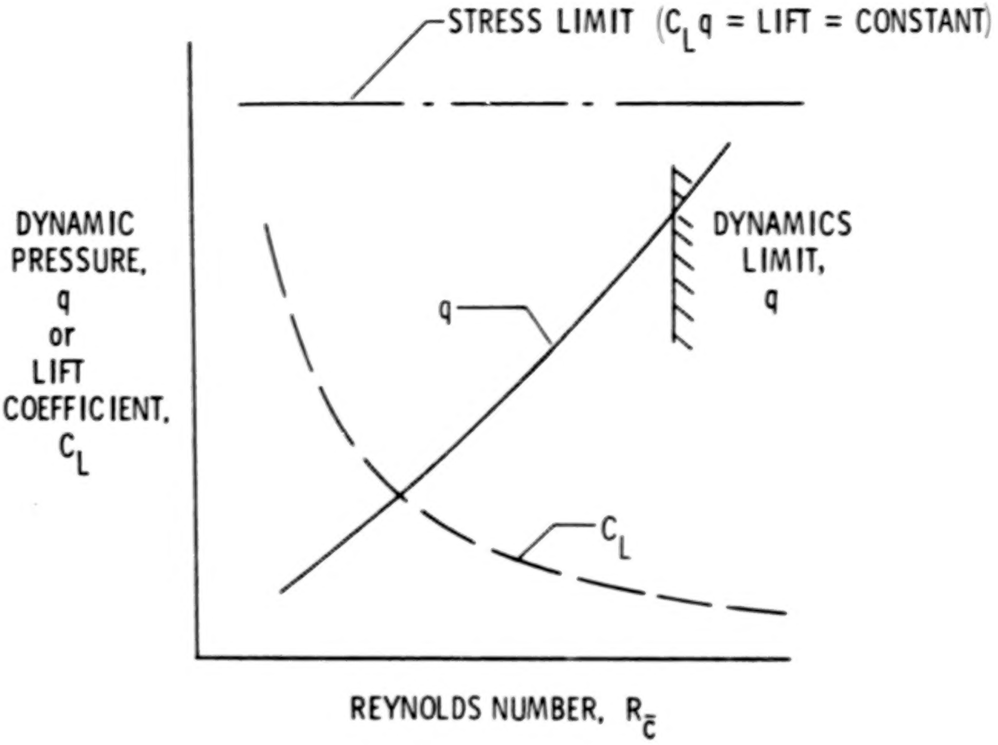
STRESS LIMIT ($C_L q$ = LIFT = CONSTANT)
DYNAMIC PRESSURE, q or LIFT COEFFICIENT, C_L
q
DYNAMICS LIMIT, q
C_L
REYNOLDS NUMBER, $R_{\bar{c}}$

Figure 7.- Model-imposed limits on matching aircraft flight conditions.

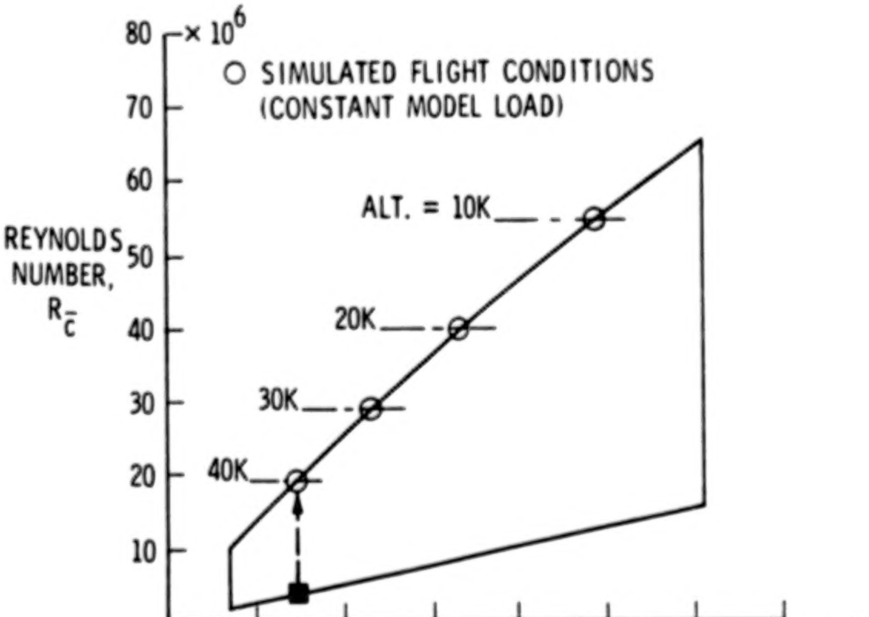

Figure 8.- NTF operating envelope at M = 0.90 for Pathfinder II. $\bar{c}$ = 5.6 in.

MODEL SYSTEMS CRITERIA

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Design criteria have been developed specifically for model systems to be tested at high Reynolds number in a cryogenic environment. More specifically, the criteria are aimed at identifying those special requirements and alternate criteria for utilizing the high Reynolds number facility (the National Transonic Facility) at Langley Research Center. The criteria are set forth in LHB 8850.1, Wind Tunnel Model Systems Criteria (Langley Research Center, Sept. 1981). This document is Langley policy, and its requirements are mandatory for all model systems to be tested at Langley. The principal revisions to this document are given in the illustrations.

Of particular interest to the users of the National Transonic Facility (NTF) is Chapter VII of this document, which sets forth the special requirements and alternate criteria for NTF models. Principal revisions to this chapter include a relaxation of the design safety factor to 1.5 on yield or 2 on ultimate (via waiver), and a material impact strength of 25 ft-lb. Relaxation of the safety factors will allow testing at high dynamic pressures using high-strength cryogenically acceptable alloys. The Charpy requirement is aimed at selecting materials for use at high stress levels, which requires very tough materials to avoid brittle fracture failure. The Charpy V-notch testing is a comparatively easy test certification. However, there are problems with the Charpy requirement in that it does not provide sufficient data for a fracture mechanics analysis. The parameter K_{Ic} (plane strain fracture toughness) is needed for quantitation studies, but it is difficult to obtain. It is recognized that a more definitive criterion is needed for different alloys. Also, the 25 ft-lb requirement should not be used to eliminate other materials such as aluminum or composites, some of which are quite suitable for cryogenic models if the appropriate fracture assessment is made for the specific application.

The use of lower safety factors requires that a fracture mechanics analysis be made for the reasons given in the illustrations. Such an analysis can be used to establish screening flaw sizes for nondestructive evaluation (NDE), which in most cases should satisfy the requirement. (However, if one or more flaws are found, this will require a life prediction based on crack propagation analyses.)

Testing at much higher dynamic pressures (compared to conventional high-speed models) requires that added attention be given to aeroelastic stability, both static (divergence) and dynamic (flutter). For this reason a safety factor of 2 is required against divergence and flutter. Insofar as the selection of analysis methods, that is left up to the user but should reflect state-of-the-art methodology and sufficient rigor to demonstrate a high degree of confidence.

In summary, criteria are defined which are intended to insure structural integrity of model systems and at the same time provide sufficient flexibility in their applications. It is recognized that certain criteria need to be more definitized, but at this stage criteria are by necessity more stringent in that high Reynolds number cryogenic testing is without precedent. However, as operational and design experience is gained, it is anticipated that a maturing of the criteria will occur, and more definitive standards will be developed.

DESIGN CRITERIA PHILOSOPHY

- BUILD UPON EXISTING CRITERIA FOR CONVENTIONAL WIND TUNNEL MODELS
- ESTABLISH SPECIAL REQUIREMENTS AND ALTERNATE CRITERIA FOR UTILIZING HIGH Re FACILITY (NTF) CAPABILITY
  - CRYO TEMP.
  - HIGH LOADS
- PROVIDE MAXIMUM FLEXIBILITY WHILE INSURING MODEL SYSTEM INTEGRITY

WIND-TUNNEL MODEL SYSTEMS CRITERIA DOCUMENT

- LHB 8850.1 DATED SEPTEMBER 30, 1981
  - SUPERCEDES USER-FURNISHED WIND-TUNNEL MODEL CRITERIA DOCUMENT LHB 8850.1 DATED OCTOBER 1976
  - INTERIM RELEASE - USER'S COMMENTS REQUESTED
  - GENERATED AS A PART OF NTF CRYO MODELS TECHNOLOGY DEVELOPMENT PROGRAM
- PRINCIPAL REVISIONS INCORPORATED IN NEW DOCUMENT
  - APPLIES TO ALL WIND TUNNEL MODELS AND MODEL SUPPORT SYSTEMS TESTED AT LaRC
  - SETS FORTH SPECIAL REQUIREMENTS FOR HIGH Re MODELS (CHAPTER VII)
  - REQUIRES QUALITY ASSURANCE PLAN
  - DEFINES WAIVER APPROVAL PROCEDURE
- IMPLEMENTATION RESPONSIBILITY - FACILITY SAFETY HEAD

PROBLEMS WITH CHARPY REQUIREMENT

- NOT ALWAYS A TRUE MEASURE OF TOUGHNESS NOR DOES IT PROVIDE INFORMATION NEEDED FOR FRACTURE MECHANICS ANALYSIS - K_{Ic} (PLANE STRAIN FRACTURE TOUGHNESS) IS A MORE SOPHISTICATED PARAMETER, CAN BE USED QUANTITATIVELY BUT DIFFICULT TO OBTAIN
- CHOSEN TO BE CONSERVATIVE BUT MAY BE DIFFICULT TO MEET - e.g., Ni 40, VASCO 200 MATERIAL EXPERIENCE TO DATE
- SHOULD NOT BE USED TO ELIMINATE OTHER MATERIALS WHICH ARE ACCEPTABLE FOR CRYOGENIC USE SUCH AS
    - ALUMINUM ALLOYS
    - COMPOSITES
- MORE DEFINITIVE CRITERIA ARE NEEDED FOR DIFFERENT ALLOY GROUPS

SPECIAL REQUIREMENTS AND ALTERNATE CRITERIA
(REF.: CHAPTER VII - LHB8850.1)

- UNIQUENESS
    - SETS FORTH ADDITIONAL REQUIREMENTS AND/OR EXCEPTIONS TO GENERAL CRITERIA FOR UNUSUALLY HIGH LOADS AND/OR EXTREME TEST TEMPERATURES
- ALLOWABLE STRESS - SAFETY FACTOR OF 3 ON YIELD OR 4 ON ULTIMATE (AS BUILT CONDITION, AT TEST CONDITION, INCLUDES THERMAL LOADS)
    - MAY BE RELAXED BY WAIVER TO 1.5 ON YIELD OR 2 ON ULTIMATE
- FATIGUE - SAFE LIFE DESIGN WITH SAFETY FACTOR OF 2 (UNCHANGED FROM PAST LaRC PRACTICE)

SPECIAL REQUIREMENTS AND ALTERNATE CRITERIA (CONTINUED)

- FRACTURE TOUGHNESS
  - CHARPY V-NOTCH IMPACT STRENGTH - 25 FT.-LBS. AT TEST TEMP. - AS BUILT CONDITION
    - USE AS A SCREENING OR RANKING FACTOR IN MATERIAL SELECTION - AIM IS TO SELECT TOUGH, FRACTURE RESISTANT MATERIAL
    - CHARPY DATA GENERALLY AVAILABLE FOR HIGH STRENGTH ALLOYS - CAN WRITE IN SPEC.
    - COMPARATIVELY EASY TEST CERTIFICATION
    - DERIVED PRIMARILY FOR HIGH STRENGTH METALLIC ALLOYS NEEDED FOR HIGH LOADS APPLICATION
  - REQUIRES FRACTURE MECHANICS ANALYSIS (ASSESSMENT)
    - ESTABLISH SCREENING FLAW SIZE FOR DESTRUCTIVE EXAMINATION
    - LIFE PREDICTION FOR FLAW EXISTENCE (OR ASSUMED TO EXIST) AT CRITICAL LOCATION(S)
  - WHY NEEDED?
    - LOW TEMP. INCREASES PROBABILITY OF BRITTLE FRACTURE
    - HIGH LOADS APPLICATION IS LIKELY TO REQUIRE ALLOYS THAT ARE FLAW SENSITIVE
    - HIGH STRESS STATES TEND TO INCREASE CRACK INITIATION AND GROWTH RATE
    - HIGH COST OF MODEL FAILURE AND TUNNEL DAMAGE

SPECIAL REQUIREMENTS AND ALTERNATE CRITERIA
(CONCLUDED)

- SYSTEM AEROELASTIC STABILITY
    - DIVERGENCE - SAFETY FACTOR OF 2 (UNCHANGED)
        - DEMONSTRATED BY IN-DEPTH ANALYSIS
        - SYSTEM STIFFNESS VERIFICATION (WHERE POSSIBLE)
    - FLUTTER - SAFETY FACTOR OF 2 (NEW)
        - DEMONSTRATED BY IN-DEPTH ANALYSIS
        - VIBRATION MODES VERIFICATION (WHERE POSSIBLE)

- ANALYSIS CONSIDERATIONS -

- SELECTION OF METHODS UP TO USER
- WHAT IS INTENT OF "STATE OF THE ART" AND "IN DEPTH"
    - GET YOUR ATTENTION - NO DESIGN PRECEDENTS
    - WORK TO HIGH LOADS, LOW MARGINS, NEED CONFIDENCE IN DESIGN → MORE RIGOROUS ANALYSIS
    - CONSIDER TOTAL SYSTEM EFFECTS, e.g., STRUCTURAL JOINT EFFECTS, BALANCE FLEXIBILITY, TOTAL AERO LOADS, DYNAMIC RESPONSE, THERMAL
- EXTENT OF ANALYSES? HOW MUCH IS ENOUGH?
    - MUST SATISFY REQUIREMENTS FOR MODEL INTEGRITY REPORT
    - DETERMINE REQUIREMENTS "A PRIORI" IF POSSIBLE
    - WILL VARY WITH MODEL COMPLEXITY, TEST REQUIREMENTS, ETC.
    - WORK CLOSELY WITH LaRC - FLEXIBILITY IS THERE TO GET WAIVERS

- SUMMARY -

- WIND TUNNEL MODEL SYSTEMS CRITERIA DOCUMENT (LHB 8850.1) DATED SEPTEMBER 30, 1981, PUBLISHED AND SHOULD BE USED FOR CRYOGENIC MODELS SYSTEMS DESIGN
- DOCUMENT IS AN INTERIM RELEASE - USER'S COMMENTS ARE SOLICITED
- DOCUMENT IS INTENDED TO INSURE INTEGRITY OF MODEL SYSTEMS AND ALLOW MAXIMUM FLEXIBILITY
- REQUIREMENTS FOR CRYOGENIC MODEL SYSTEMS ARE BY NECESSITY MORE STRINGENT
- LaRC RECOGNIZES THAT CERTAIN CRITERIA NEED TO BE MORE DEFINITIZED AND IS WORKING TOWARD THAT END VIA
    - APPLICATION TO CURRENT MODELS IN SYSTEM (WORKS THE PROBLEM)
    - PLANNED R & D ACTIVITIES

NTF USER OPERATIONS REQUIREMENTS

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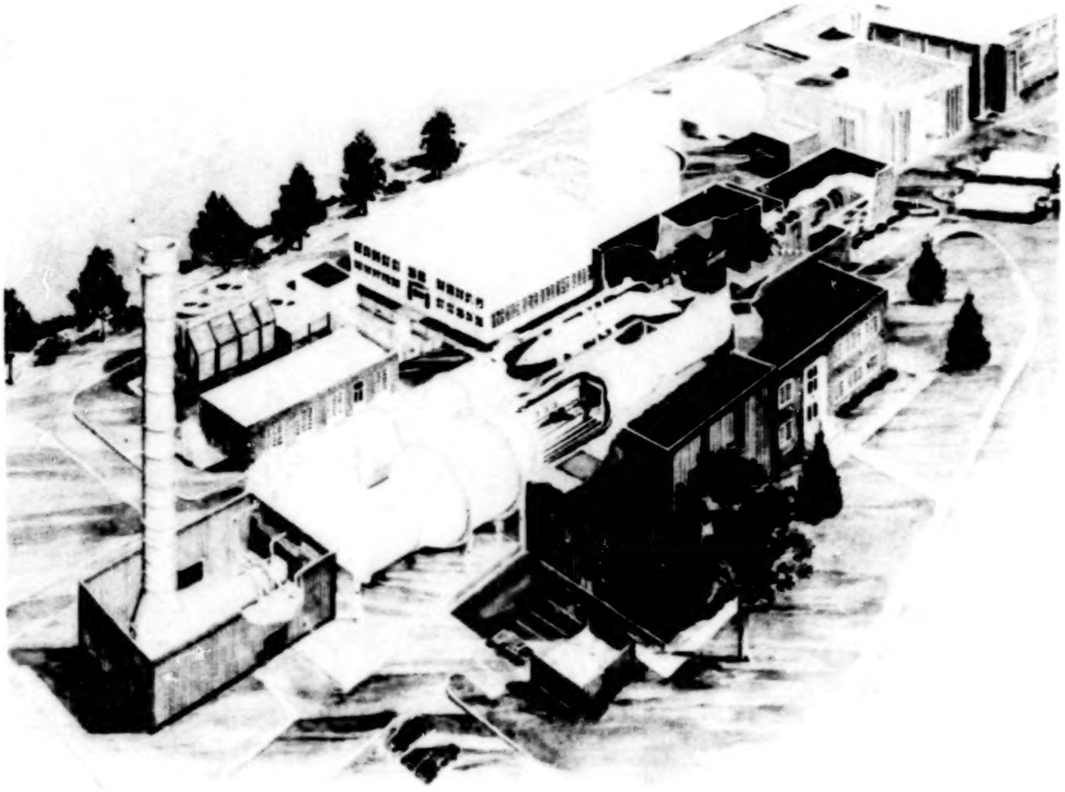
A procedure that must be followed for a model to be accepted for testing in the NTF has been defined and is outlined in this paper. The four steps in this procedure are: planning meeting; pre-test conference; model receipt, assembly and checkout; and model installation and test. Areas of discussion at the planning meeting, which should be held prior to final design, include: general discussion of model and tests; need for additional reviews (such as preliminary and/or critical design reviews); and requirements for models as outlined in LHB 8850.1 (Wind-Tunnel Model Systems Criteria, Langley Research Center, September 1981). The pretest conference should occur at least 8 weeks prior to model delivery to NTF, and at this meeting the readiness of the model will be reviewed.

Also described in this paper is the model preparation and model handling equipment available at the NTF. There are three model assembly rooms which are secure and have direct electronic hookups to the NTF control room and computer complex. While in the model assembly room the model may be static check loaded and cryogenically cycled. Model handling carts are available for transporting the model from the model preparation room to the test section.

Finally this paper describes the model access system and shows that the turnaround time for a model modification while the model is installed in the tunnel is on the order of 1-1/2 hours plus the time required to make the model modification.

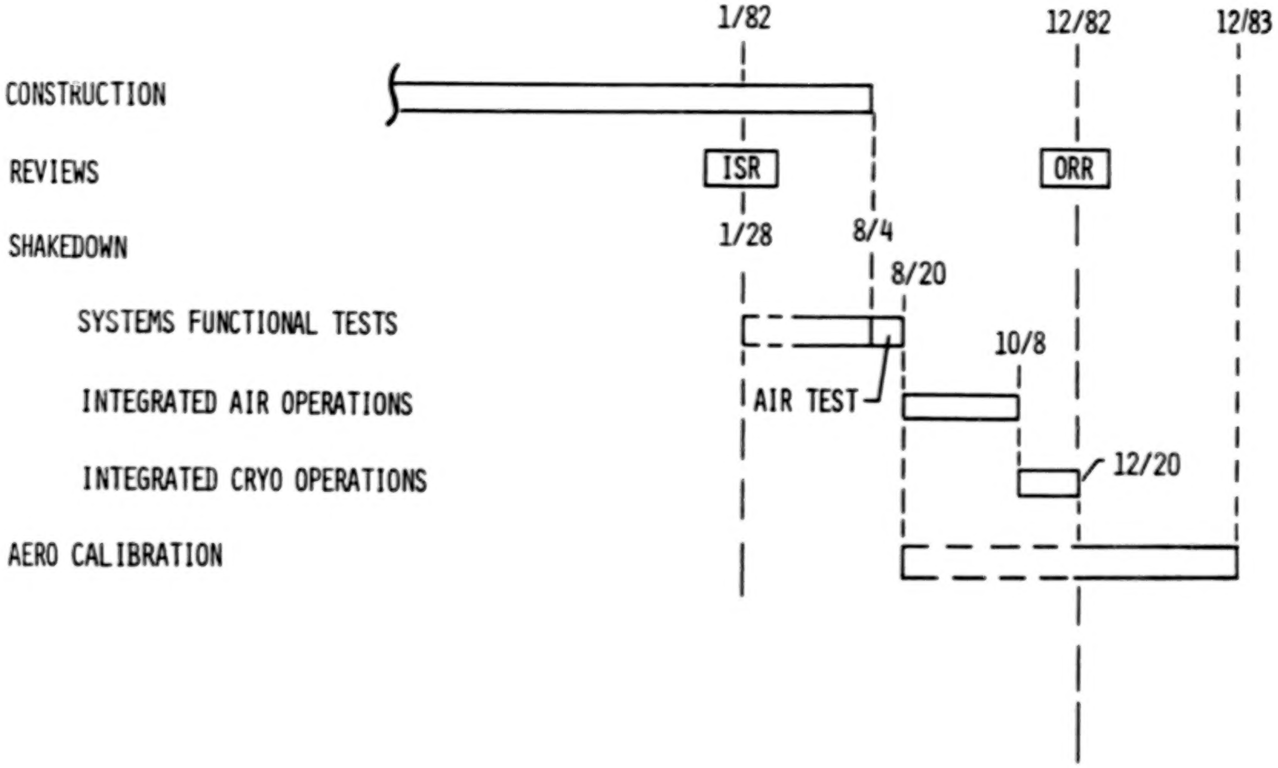
ARTIST'S CONCEPT OF NATIONAL TRANSONIC FACILITY



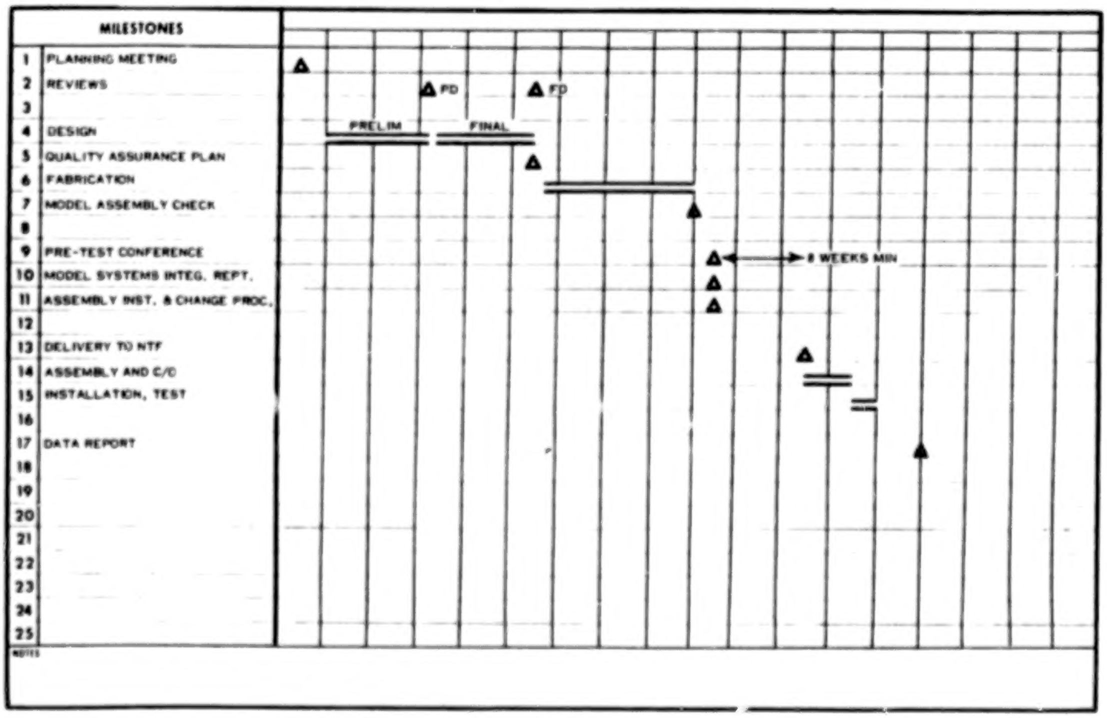
NTF CHARACTERISTICS

TEST SECTION SIZE	2.5 METERS SQUARE
PRESSURE RANGE	1 TO 9 BARS
TEMPERATURE RANGE	78 TO 340 K
MACH NUMBER RANGE	.2 TO 1.2
DRIVE POWER	9×10^7 WATTS (6.6×10^7 CONTINUOUS)
REYNOLDS NUMBER	120×10^6 ($M=1$, $\bar{c}=.25M$)
TEST GAS	AIR, NITROGEN

NTF MASTER SCHEDULE



1/16 SCALE MODEL OF THE FXXX AIRPLANE



NTF OPERATIONS

(MODEL FLOW PATH)

- PLANNING MEETING
  - MODEL SYSTEMS INTEGRITY REPORT
  - WAIVERS
  - QUALITY ASSURANCE PLAN
- PRE-TEST CONFERENCE
- MODEL RECEIPT, ASSEMBLY & CHECKOUT
  - MODEL ASSEMBLY ROOM
  - BACKSTOPS
  - WEIGHT BASKETS
  - CRYOGENIC CHAMBER
  - MODEL HANDLING CART
- MODEL INSTALLATION AND TEST
  - PLENUM/MODEL ACCESS
  - TEST SEQUENCE

PLANNING MEETING

- OBJECTIVES
- TIME FRAME
- MODEL SIZE, CHARACTERISTICS
- GENERAL INSTRUMENTATION, HARDWARE PLAN
- DESIGN LOADS CRITERIA
- MODEL SYSTEMS INTEGRITY REPORT
- QUALITY ASSURANCE PLAN
- ESTABLISH POINTS OF CONTACT

MODEL SYSTEMS INTEGRITY REPORT

- DESIGN LOADS CRITERIA
- STRESS ANALYSIS
- FRACTURE MECHANICS ANALYSIS
- FLUTTER ANALYSIS
- DIVERGENCE ANALYSIS
- STRUCTURAL JOINT ASSEMBLY DETAILS AND STIFFNESS
- QUALITY INSPECTION REPORTS
- MATERIALS PROPERTIES CERTIFICATION
- N.D.E. EXAMINATION RESULTS
- VALIDATION OF USE OF CERTIFIED MATERIALS
- AS-BUILT CHARPY IMPACT & MECH. STR. PROPERTIES
- AS-BUILT DETAIL DRAWINGS

WAIVERS

DEVIATIONS FROM LHB 8850.1 CRITERIA REQUIRE SUBMITTAL OF WRITTEN REQUESTS TO THE FACILITY SAFETY HEAD. THE FACILITY HEAD WILL BE RESPONSIBLE FOR THE ANALYSIS, EVALUATION, AND DOCUMENTATION OF THE DISPOSITION OF THE WAIVER REQUEST.

QUALITY ASSURANCE PLAN

- REQUIRED
- SHOULD CONTAIN PROVISIONS FOR DEFINING AND VERIFYING ARTICLE AND MATERIAL QUALITY THROUGHOUT ALL OPERATIONS
  - PROCUREMENT
  - FABRICATION
  - TEST
  - DELIVERY
  - INSTALLATION
- SHOULD INSURE MAINTENANCE OF QUALITY WITH:
  - RECORDS
  - INSPECTION
  - TEST RESULTS

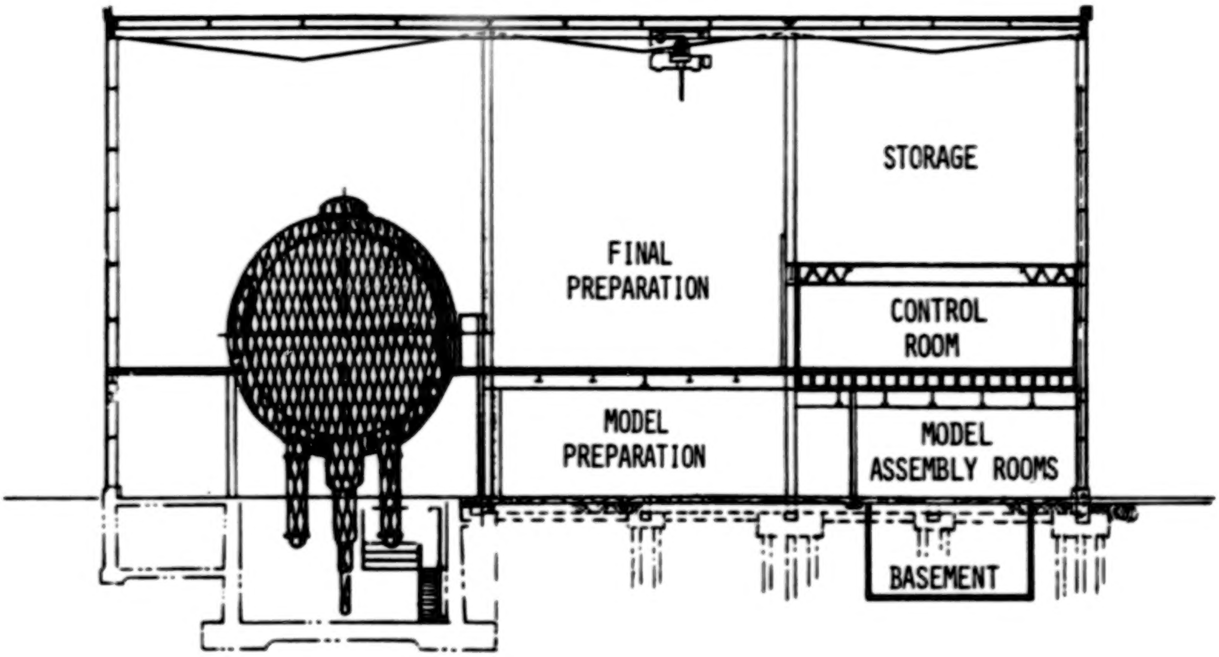
PRE-TEST CONFERENCE

- ESTABLISH TEST PROGRAM
- ESTABLISH INSTRUMENTATION/CALIBRATION REQUIREMENTS
- ESTABLISH DATA ACQUISITION/REDUCTION PLAN
- IDENTIFY TEST TEAM
  - RESEARCH PROJECT ENGINEERS
  - DATA ACQUISITION/REDUCTION
- ESTABLISH MODEL/TEST SCHEDULE
- CHECK OFF MODEL SYSTEMS INTEGRITY REPORT
- CHECK OFF MODEL QUALITY ASSURANCE

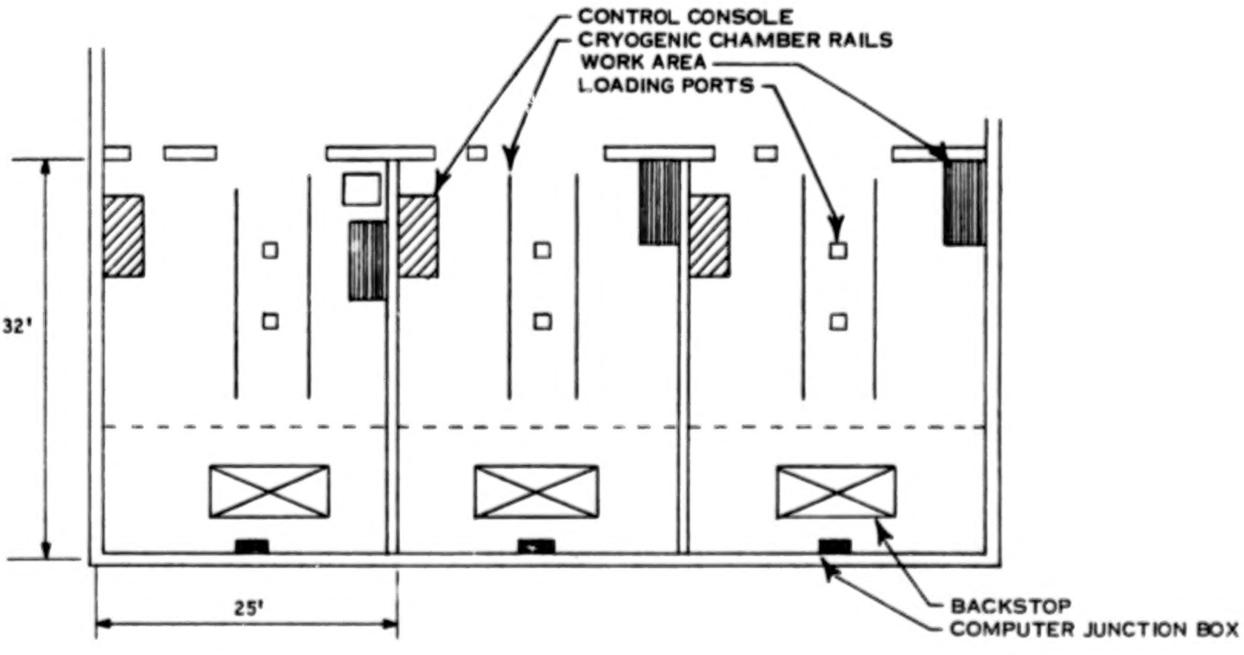
BEST DOCUMENT AVAILABLE

NATIONAL TRANSONIC FACILITY

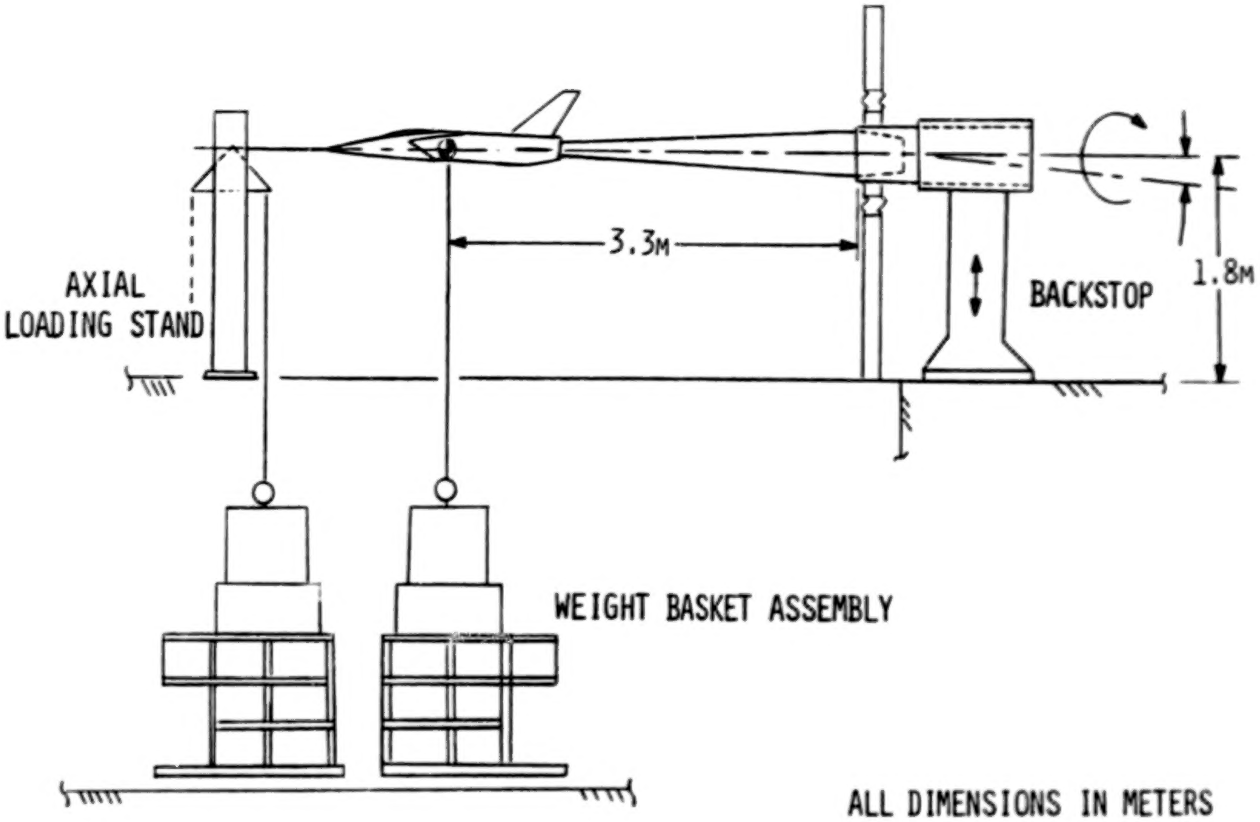
BUILDING


STORAGE
FINAL PREPARATION
CONTROL ROOM
MODEL PREPARATION
MODEL ASSEMBLY ROOMS
BASEMENT

MODEL ASSEMBLY ROOMS

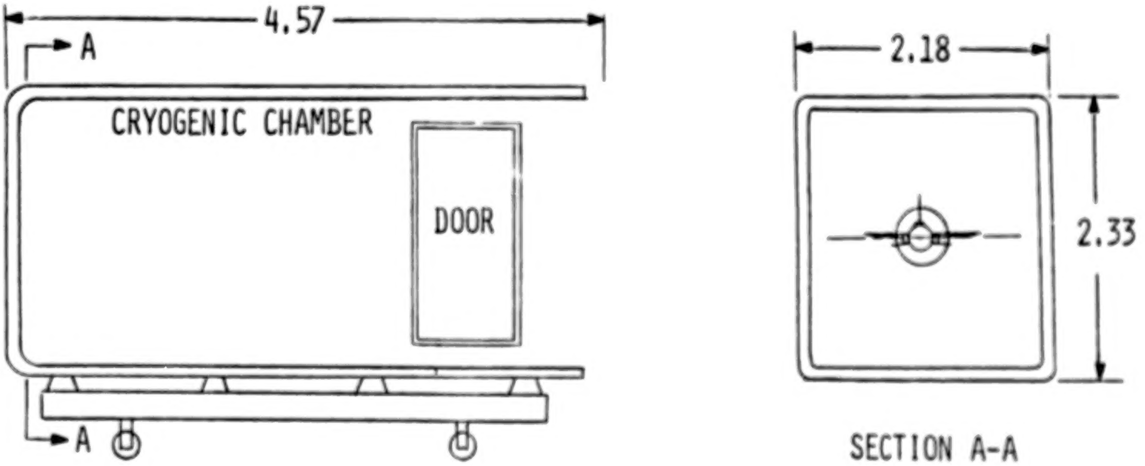

CONTROL CONSOLE
CRYOGENIC CHAMBER RAILS
WORK AREA
LOADING PORTS
32'
25'
BACKSTOP
COMPUTER JUNCTION BOX

MODEL CHECKOUT EQUIPMENT


AXIAL
LOADING STAND
3.3M
BACKSTOP
1.8M
WEIGHT BASKET ASSEMBLY

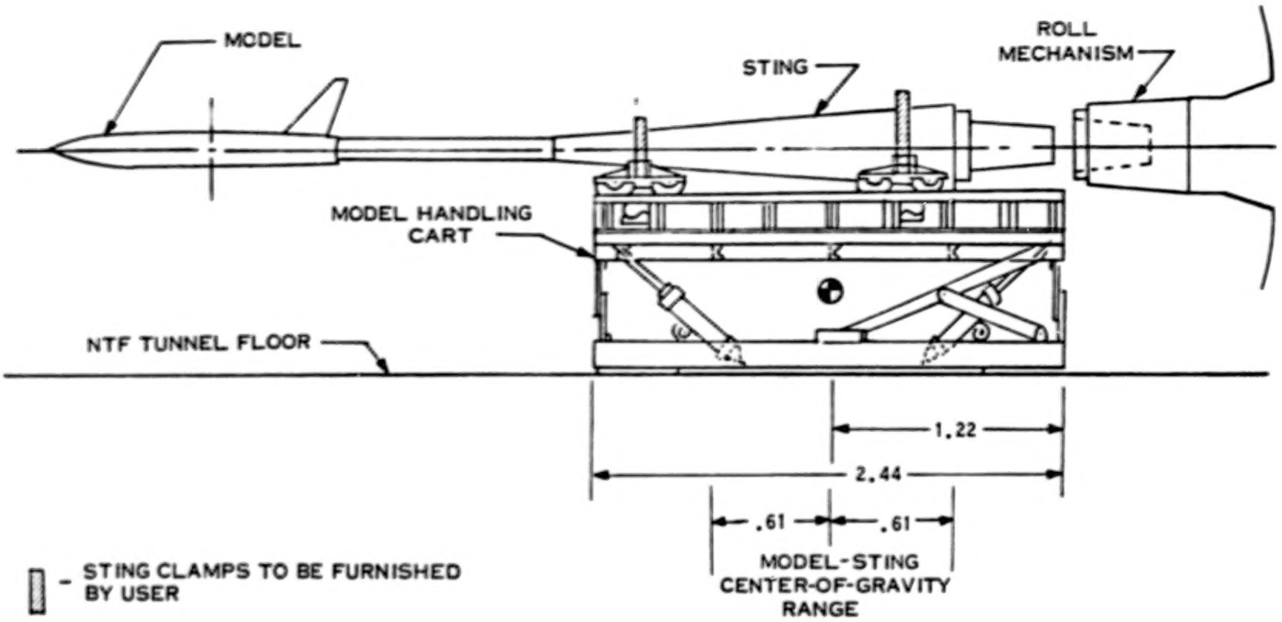
ALL DIMENSIONS IN METERS

SCHEMATIC OF CRYOGENIC CHAMBER

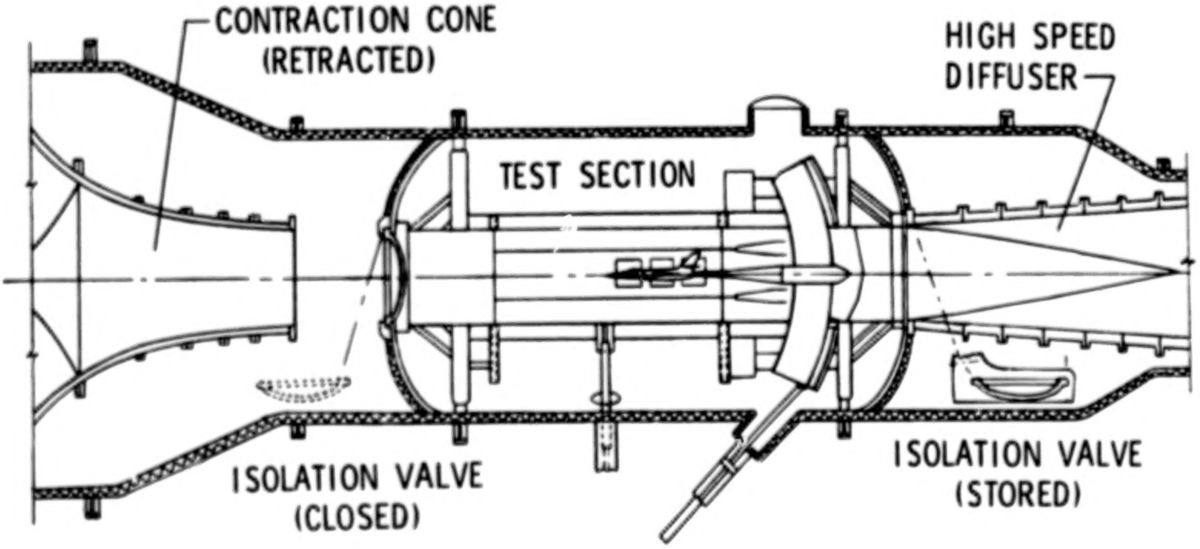

4.57
A
CRYOGENIC CHAMBER
DOOR
A
2.18
2.33

SECTION A-A

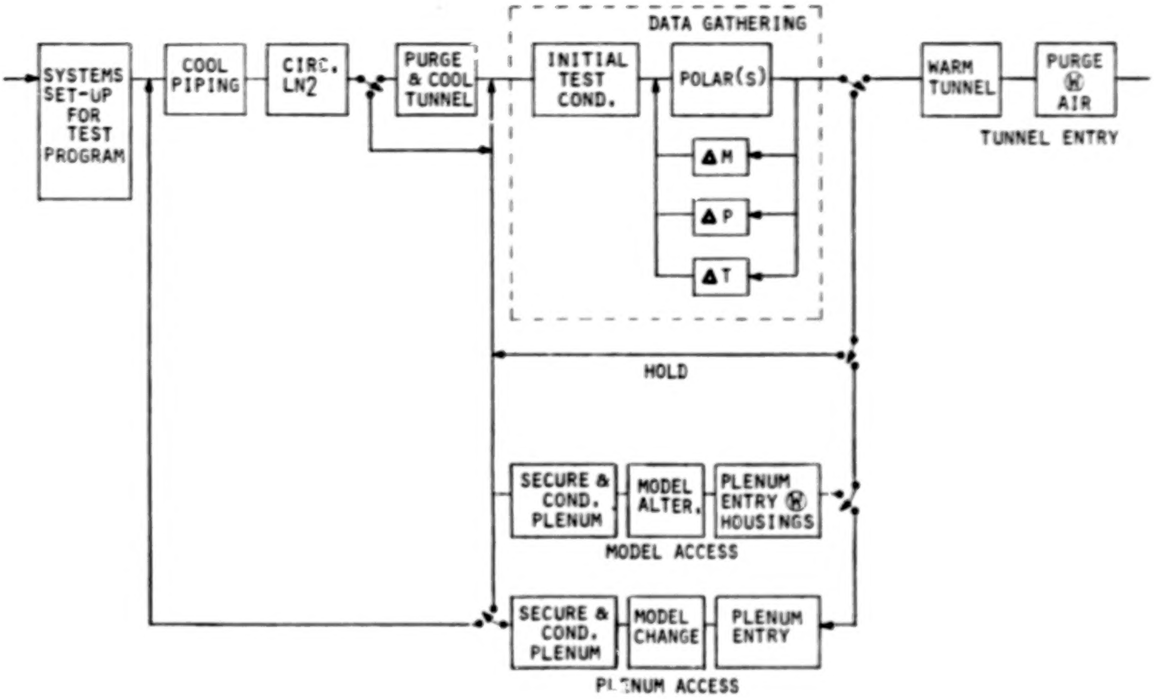
MODEL-STING SUPPORT SYSTEM


MODEL
STING
ROLL MECHANISM
MODEL HANDLING CART
NTF TUNNEL FLOOR
1.22
2.44
.61
.61
MODEL-STING CENTER-OF-GRAVITY RANGE
▨ - STING CLAMPS TO BE FURNISHED BY USER

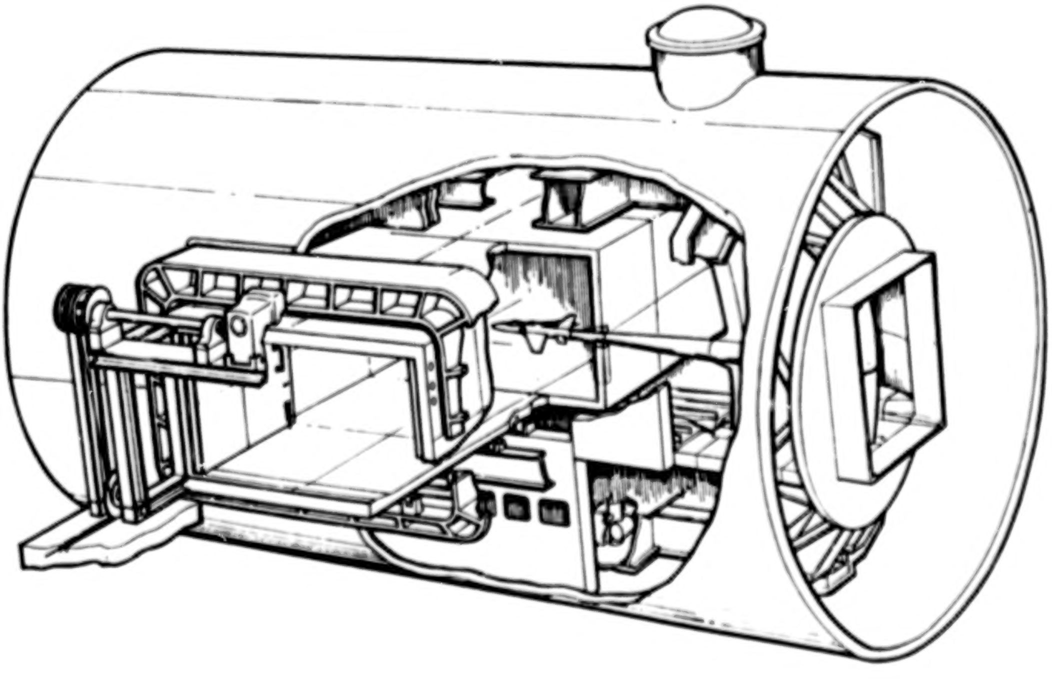
NATIONAL TRANSONIC FACILITY TEST PLENUM ISOLATION SYSTEM


CONTRACTION CONE (RETRACTED)
HIGH SPEED DIFFUSER
TEST SECTION
ISOLATION VALVE (CLOSED)
ISOLATION VALVE (STORED)

NTF OPERATION


SYSTEMS SET-UP FOR TEST PROGRAM
COOL PIPING
CIRC. LN2
PURGE & COOL TUNNEL
DATA GATHERING
INITIAL TEST COND.
POLAR(s)
ΔM
ΔP
ΔT
WARM TUNNEL
PURGE Ⓗ AIR
TUNNEL ENTRY
HOLD
SECURE & COND. PLENUM
MODEL ALTER.
PLENUM ENTRY Ⓗ HOUSINGS
MODEL ACCESS
SECURE & COND. PLENUM
MODEL CHANGE
PLENUM ENTRY
PLENUM ACCESS

MODEL ACCESS SYSTEM



MODEL ACCESS - ACTUATING TIMES

FUNCTION	TIME
CONDITION PLENUM	18 MIN
INSERT TUBES	3 MIN
CONDITION TUBES/WARM MODEL	37 MIN
CHANGE/SERVICE MODEL	VARIABLE
PREPARE FOR TUBE EXTRACTION	5 MIN
RETRACT TUBES	3 MIN
RETURN TO OPERATING CONDITIONS	18 MIN
TOTAL	84 MIN + VARIABLE

ASPECTS OF FRACTURE MECHANICS IN CRYOGENIC MODEL DESIGN
PART I - FUNDAMENTALS OF FRACTURE MECHANICS

C. Michael Hudson
NASA Langley Research Center
Hampton, Virginia

This presentation provides a fundamental introduction to the use of fracture mechanics for predicting fracture and fatigue crack growth in metals. First, consider figure 1. The stresses (σ_y, σ_x, τ_{xy}) at any point in the vicinity of a crack tip can be defined in terms of three parameters. These parameters are (1) r, the distance from the crack tip to the point under consideration; (2) a function of θ, the angle between the x axis and r; and (3) K_I, the stress intensity factor. The term K_I is given by

$$K_I = S\sqrt{\pi a} \tag{1}$$

where S is the applied stress and a is one-half the length of the crack, for the following stress and configuration conditions:

1. A through-the-thickness crack
2. An infinite-width plate
3. A uniformly distributed stress

(Considerably more complex relationships apply for other configurations and stress conditions.)

When the failure process occurs under plane strain conditions, the value of K_{Ic} tends to remain constant for a given material and temperature. This constant value is defined as the plane strain fracture toughness of the material. For the specimen configuration shown in figure 2, K_{Ic} can be defined as

$$K_{Ic} = S\sqrt{\pi a_{critical}} \tag{2}$$

Once K_{Ic} has been determined, it can be used to predict the failure of cracked structures under plane strain conditions. (Considerably more complex procedures are required for predicting failure under plane stress conditions.) For example, if both K_{Ic} and the crack size have been determined for a certain component, the stress required to fail that component can be calculated. Similarly, the critical flaw size can be calculated if both K_{Ic} and the applied stress are known.

Many factors can affect the value of K_{Ic} for a given material. One of the most dominating factors is temperature. For many materials, the value of K_{Ic} drops precipitously with decreasing temperature. Figure 3 shows a generally linear drop in K_{Ic} with decreasing temperature for 18 Ni-(250) maraging steel (ref. 1). Figure 4 shows a rapid drop from approximately -75°F to -200°F (the transition temperature region), followed by a more gradual drop for temperatures below -200°F (ref. 1). (The data in figure 4 are from tests on A517 Grade F steel.) In both cases, the reduced values of K_{Ic} indicate that for a given stress condition, the critical flaw size decreases with decreasing temperature. This in turn indicates that greater care must be taken in inspecting structures for cryogenic applications.

Next, consider the fatigue crack growth aspects of fracture mechanics. Basic fatigue crack growth data can be generated using the center-cracked specimen shown in figure 5. This specimen is a flat sheet specimen containing a notch in the center. (Other specimen configurations are also used.) When this specimen is subjected to a cyclic loading, such as that shown in figure 6, a fatigue crack will initiate at the two ends of the notch. With continued cyclic loading, these cracks will grow towards the edges of the specimen. Figure 7 shows the variation of crack length against cycles for the loading condition shown in figure 6. The slope of this fatigue crack growth curve at any point is defined as the fatigue crack growth rate, da/dN.

The stress intensity range ΔK can also be defined for any point on the fatigue crack growth curve. This stress intensity range is given by

$$\Delta K = \sqrt{\pi a}\,(S_{max} - S_{min}) \tag{3}$$

for the specimen in figure 5 when that specimen has an effectively infinite width. The terms S_{max} and S_{min} are defined in figure 6.

Once da/dN and ΔK have been calculated for a series of points along the fatigue crack growth curves, they can be plotted against each other, as shown in figure 8 (ref. 2). The correlation of these factors is quite good.

A relationship developed by Forman et al. (ref. 3) has been found to fit the plots of da/dN against ΔK quite well. This relationship is given by

$$da/dN = \frac{C\Delta K^n}{(1 - R)K_{Ic} - \Delta K} \tag{4}$$

for plane strain conditions. In equation (4), the terms C and n are empirical constants and R is defined by

$$R = S_{min}/S_{max} \tag{5}$$

This R term can have a significant effect on fatigue crack growth.

Figure 9 (ref. 2) shows plots of da/dN against ΔK for various R values. The data for a given R value fall into discrete scatterbands. However, the scatterbands for different R values are not coincident. Generally, the higher the R value for a given value of ΔK, the higher the rate of fatigue crack growth. Forman's equation (ref. 3) fit each of these scatterbands quite well with one coefficient and one exponent (See fig. 9.) Thus Forman's equation accounts for the R value effect quite well.

Once the coefficient and exponent have been determined, equation (4) can be numerically integrated to predict the life of cracked components. Figure 10 presents the results of one set of such predictions. For this set, the coefficient and exponent were calculated using data from tests on center-cracked specimens. Equation (4) was then used to predict the number of cycles required to grow surface cracks from their initial flaw sizes to failure (ref. 4). Tests were then conducted on specimens having these flaw sizes, and the actual fatigue lives were determined. Figure 10 shows the ratios of the tests lives to predicted lives. These ratios ranged from 0.51 to 1.84. Considering that the normal scatter in fatigue crack growth rates may range from a factor of 2 to 4 under identical loading conditions, these ratios are quite good.

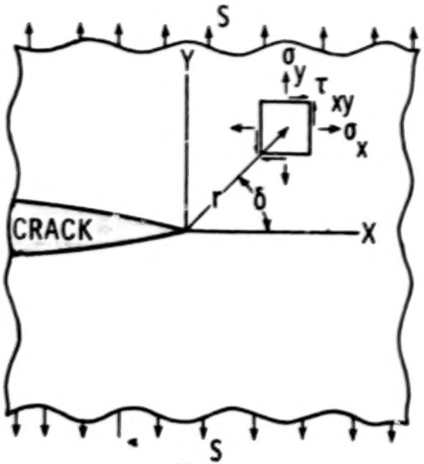
REFERENCES

1. Barson, J. M.; and Rolfe, S. T.: Correlations Between K_{Ic} and Charpy V-Notch Test Results in the Transition Temperature Range. Impact Testing of Metals, ASTM STP 466, 1970, pp. 281-302.

2. Hudson, C. Michael: Effect of Stress Ratio on Fatigue Crack Growth in 7075-T6 and 2024-T3 Aluminum-Alloy Specimens. NASA TN D-5390, 1969.

3. Forman, R. G.; Kearney, V. E.; and Engle, R. M.: Transactions, American Society of Mechanical Engineers. Series D, J. of Basic Engineering, vol. 89, no. 3, Sept. 1967, pp. 459-464.

4. Hudson, C. M.; and Lewis, P. E.: NASA Langley Research Center's Participation in a Round-Robin Comparison Between Some Current Crack-Propagation Methods. Part-Through Crack Fatigue Life Prediction, J. B. Chang, ed., ASTM STP 687, 1979, pp. 113-128.

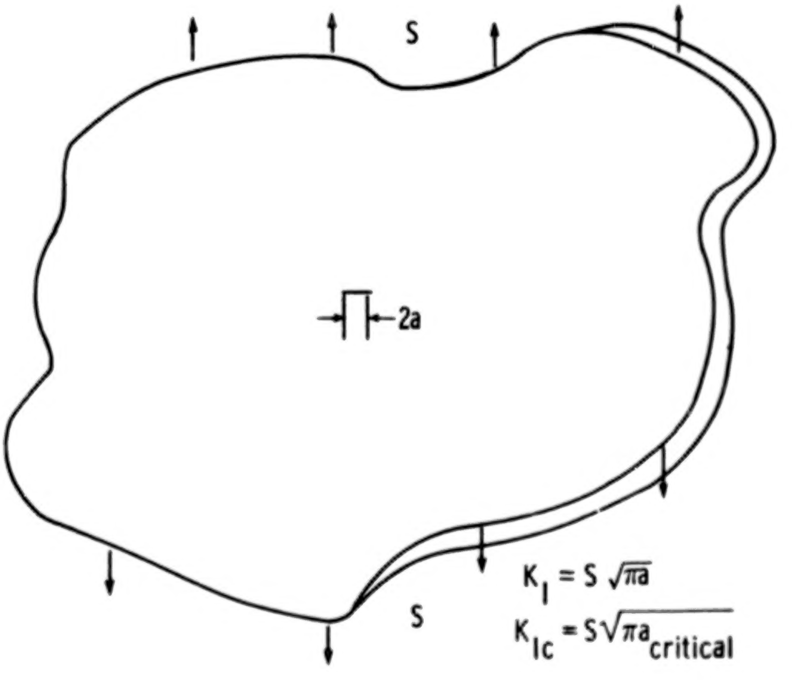

S
Y
σ_y
τ_{xy}
σ_x
r
δ
CRACK
X
S

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} f(\delta)$$

$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}} g(\delta)$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} h(\delta)$$

Figure 1.- Stress characterization in the vicinity of a crack tip.



$$K_I = S\sqrt{\pi a}$$

$$K_{Ic} = S\sqrt{\pi a_{critical}}$$

Figure 2.- Stress intensity solution for a through-the-thickness crack in an infinite-width plate.

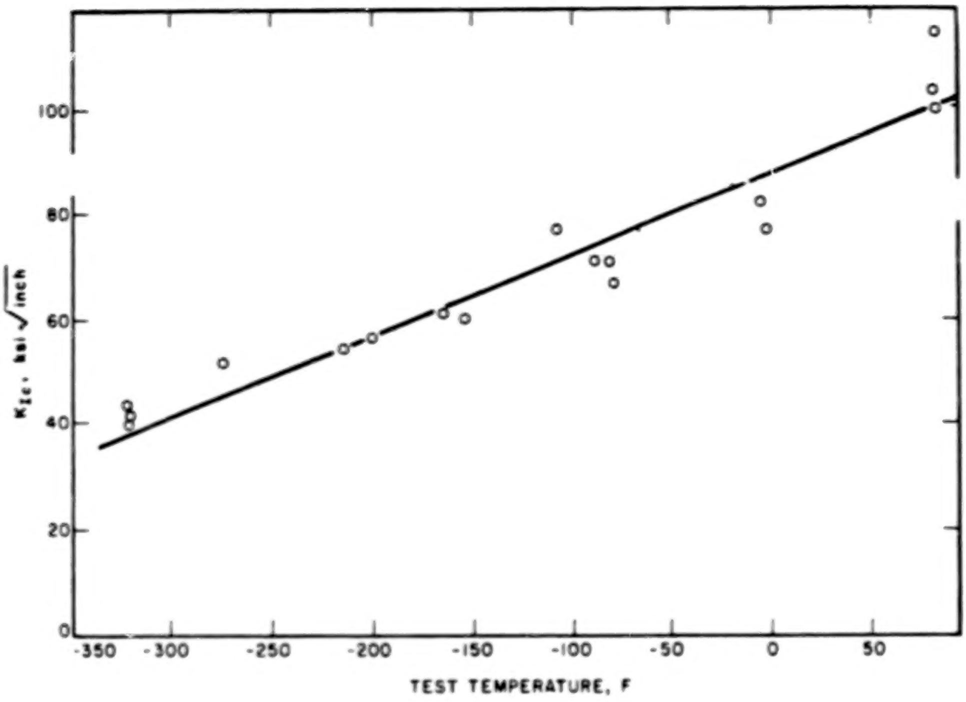


Figure 3.- Variation of K_{1c} with temperature for 18 Ni-(250) maraging steel. (From ref. 1.)

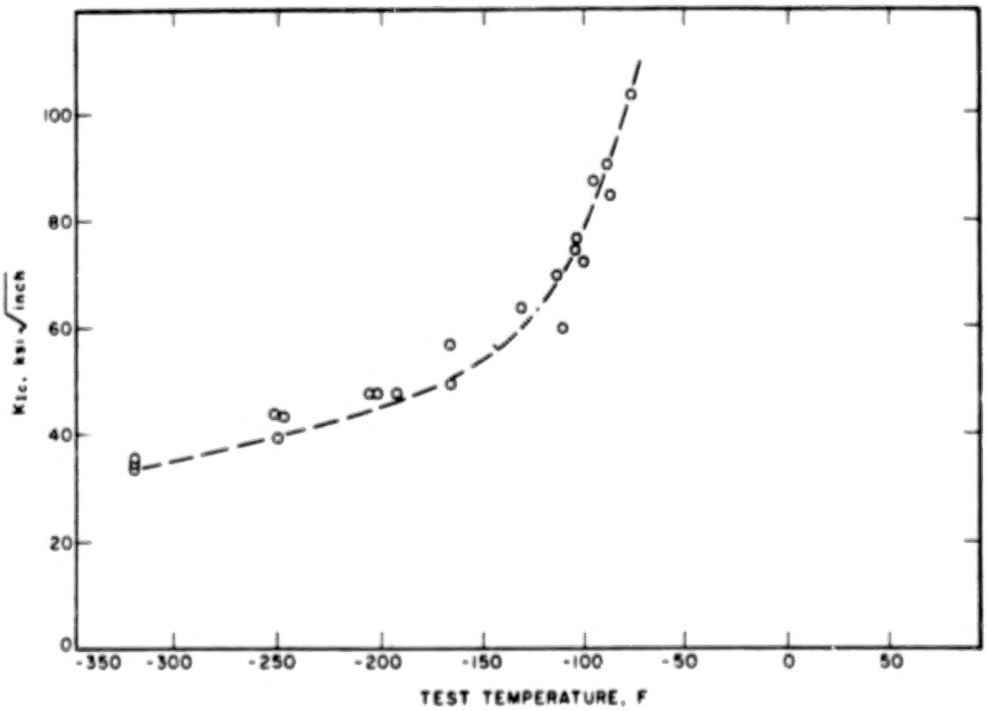


Figure 4.- Variation of K_{1c} with temperature for ASTM A517 Grade F steel. (From ref. 1.)

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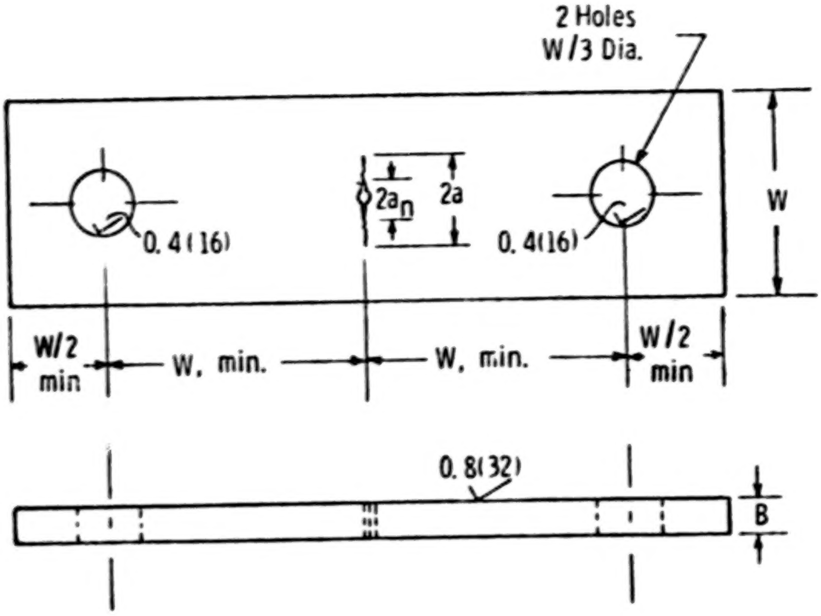
2 Holes
W/3 Dia.
$2a_n$
2a
W
0.4(16)
0.4(16)
W/2 min
W, min.
W, min.
W/2 min
0.8(32)
B

Figure 5.- Center-cracked tension specimen.

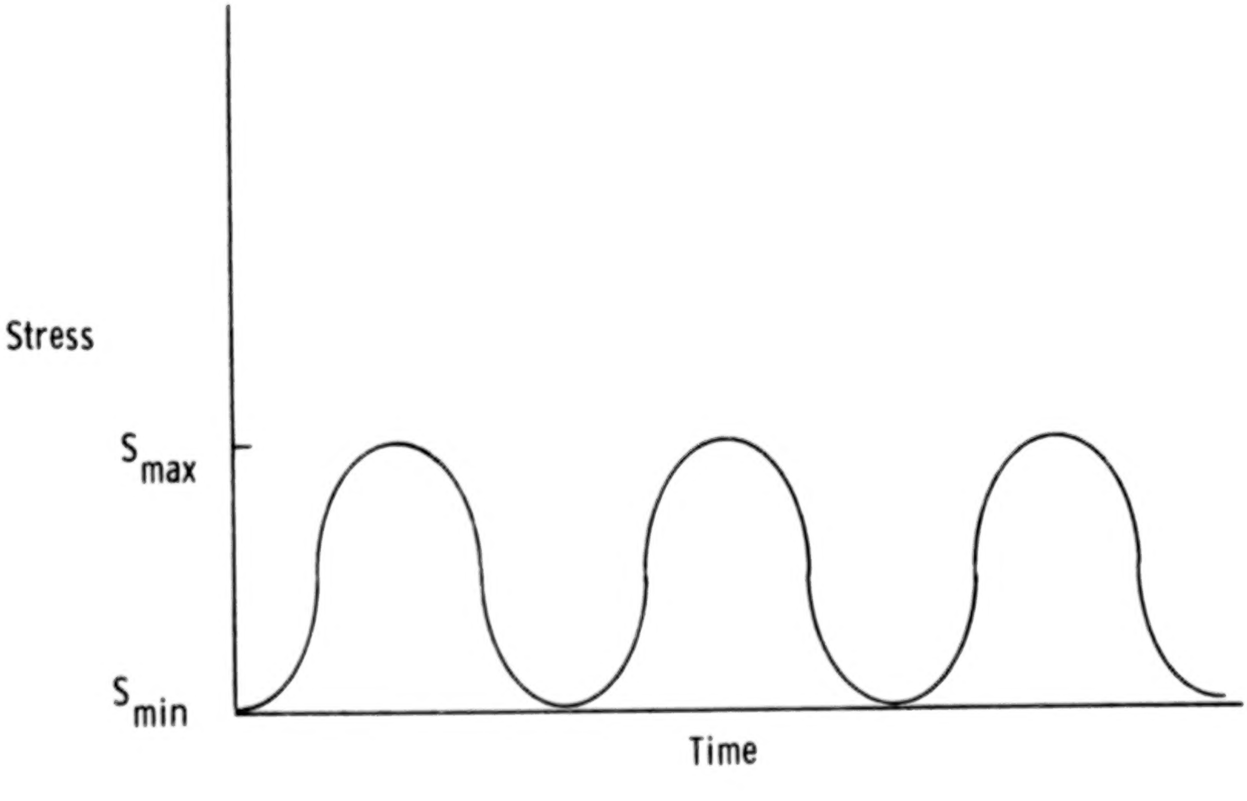

Figure 6.- Variation of stress with time.

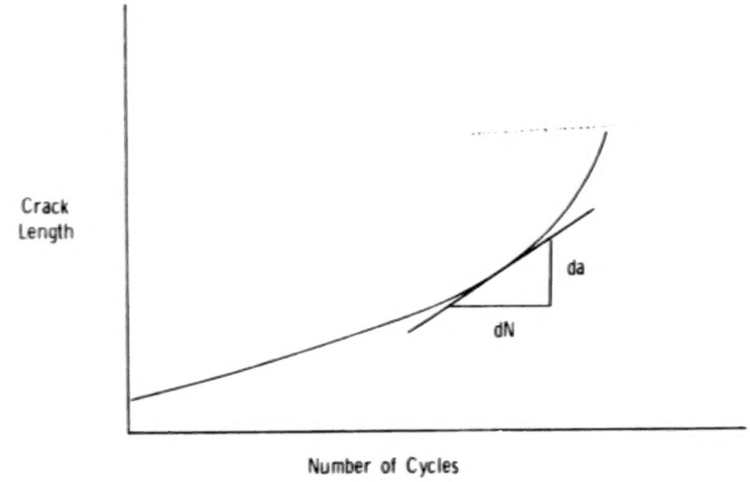

Figure 7.- Variation of crack length with number of cycles.

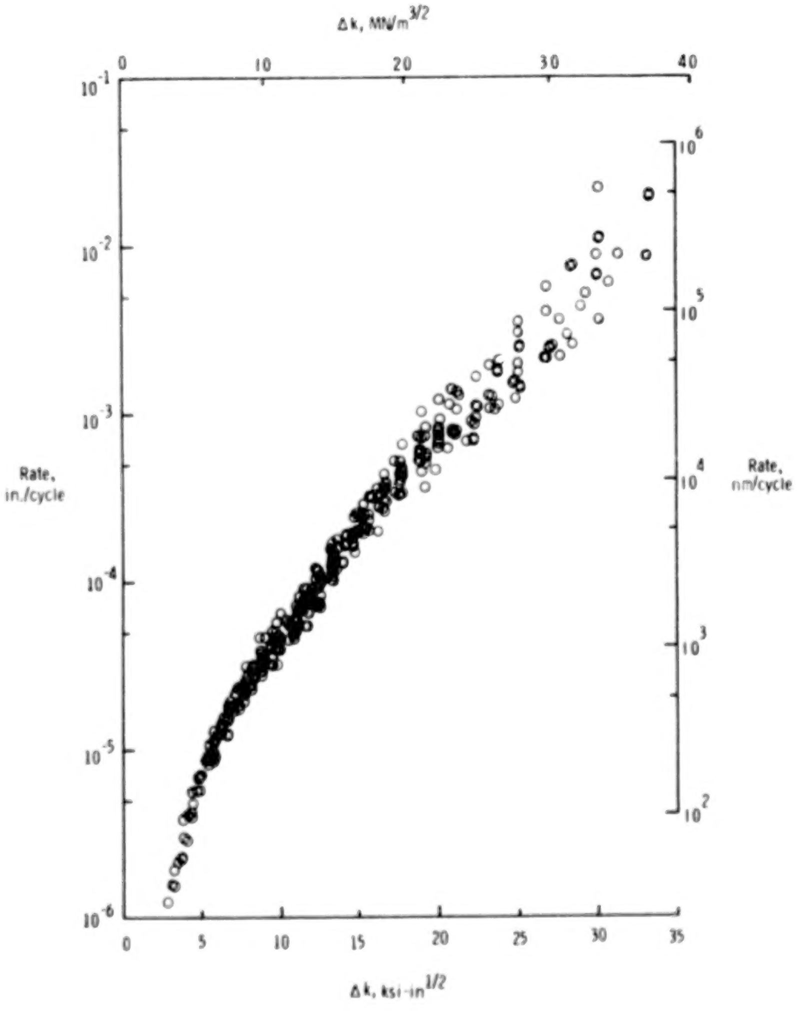

Figure 8.- Variation of da/dN with ΔK. (From ref. 2.)

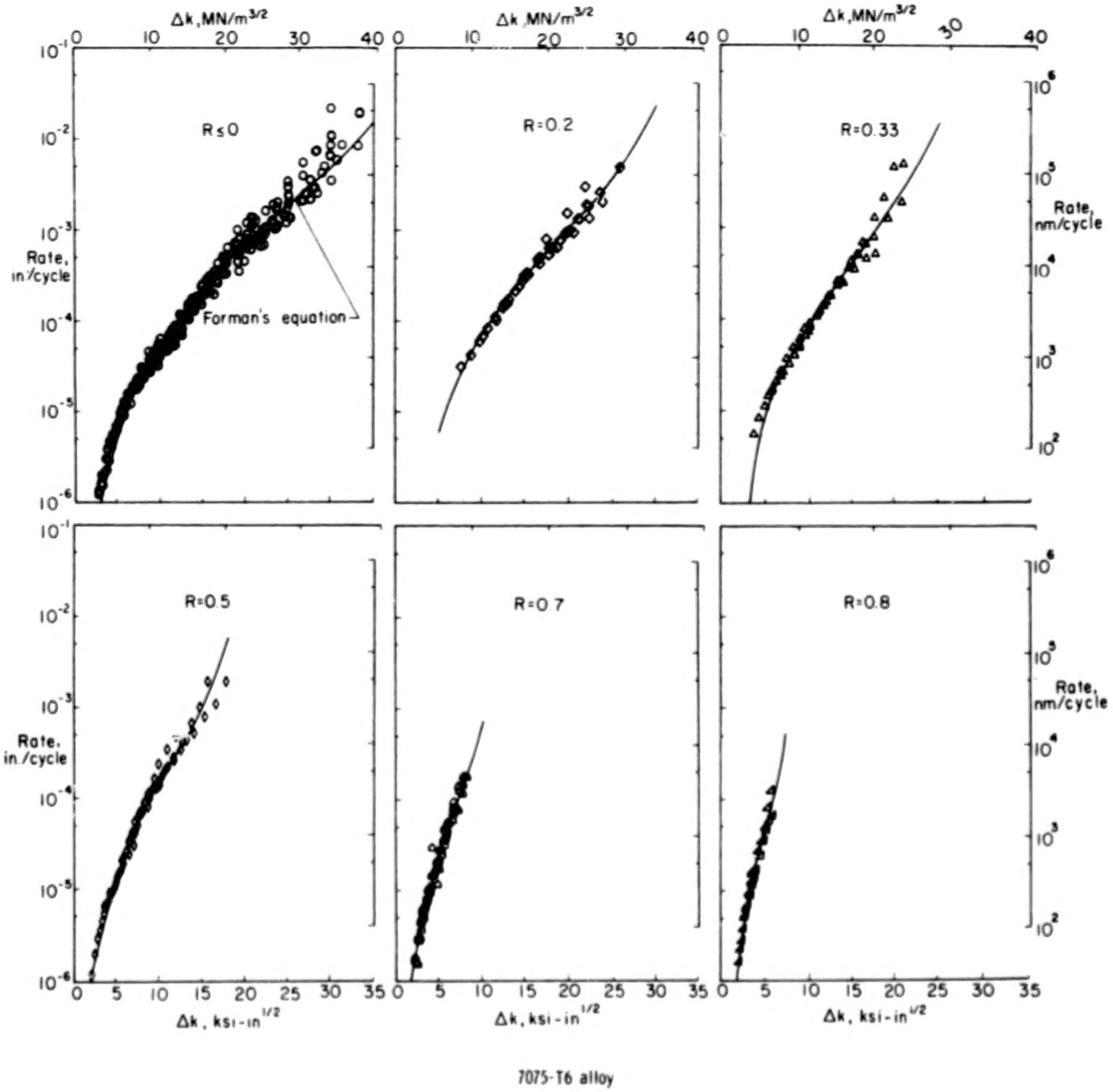

Figure 9.- Variation of da/dN with ΔK for various R values. (From ref. 2.)

SPECIMEN NUMBER	TEST LIVES/PREDICTED LIVES
23-10	1.00
23-12	1.19
23-13	1.03
23-14	1.05
23-16	0.65
23-17	0.60
23-18	1.26
23-76	0.51
37-2	1.84
37-3	0.70

Figure 10.- Ratios of test lives to predicted lives.

ASPECTS OF FRACTURE MECHANICS IN CRYOGENIC MODEL DESIGN

PART II - NTF MATERIALS

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NASA Langley Research Center
Hampton, Virginia

Over the past several years, fatigue crack growth and fracture toughness tests have been conducted at Langley for some candidate materials for use in the National Transonic Facility (NTF). These materials may be used in making strain gage balances, stings, and wind tunnel models. The purpose of this study was to present results of fatigue crack growth and fracture toughness tests conducted on three candidate materials. Fatigue crack growth and fracture toughness tests were conducted on NITRONIC 40 at room temperature and -275°F. Fracture toughness tests were also conducted on Vascomax 200 and 250 maraging steel from room temperature to -320°F (fig. 1).

NITRONIC 40 was used to make the Pathfinder I model. The model was machined from a large plate (5.5 by 44 by 60 in.)(fig. 2). After some Charpy V-notch impact energy tests (in the short transverse direction) showed somewhat low impact energies (20 to 25 ft-lb) at -275°F, a concern was expressed about the fracture toughness of the material. A fracture mechanics test program was then initiated to conduct fatigue crack growth and fracture toughness tests. Center crack tension and notch bend specimens were machined from the end of the large plate. The specimens tested the material in nearly the same direction as that of the highest stress in the wing structure. The material was tested in two conditions: as received and stress relieved (fig. 3).

The fatigue crack growth rate tests were conducted at room temperature and -275°F on three-point notch bend specimens. The crack growth rates were plotted against the stress intensity factor range ΔK, a crack tip characterizing parameter. These results showed that the crack growth rates at a given ΔK were much less at -275°F than at room temperature (about a factor of 3) (fig. 4).

The fracture toughness tests on the "as received" and "stress relieved" materials at -275°F were conducted on the center crack tension specimens. These results showed that the fracture toughness was high (estimated to be 120 ksi-in.$^{1/2}$) and that the net section stress S_n at failure was between the yield stress σ_{ys} and the ultimate tensile strength σ_u of the material, which indicated that the material was very ductile at cryogenic temperatures. The solid curve in figure 5 shows the results of a fracture analysis using the Two-Parameter Fracture Criterion (TPFC). The two fracture parameters (K_F and m) were obtained from these tests. These results show that the "elastic" fracture toughness K_{Ie} changes with crack length-to-width ratio (2a/W), but the calculated net section stresses were always greater than the yield stress. Fracture toughness tests conducted on the notch bend specimens showed similar high toughness. The fracture toughness of NITRONIC 40 exceeds the Pathfinder criteria requirement of 85 ksi-in.$^{1/2}$ at cryogenic temperatures (-275°F).

Toughness tests were also conducted on Vascomax CVM-200 and CVM-250 maraging steel from room temperature to -320°F using round and rectangular compact specimens (fig. 6). The CVM-200 and CVM-250 had a toughness of 130 and 75 ksi-in$^{1/2}$, respectively, at room temperature. At -275°F, the toughness of the CVM-200 and CVM-250 was about 80 and 60 ksi-in.$^{1/2}$, respectively. Thus, the fracture toughness of CVM-250 maraging steel does not meet the 85 ksi-in.$^{1/2}$ criteria at any temperature, and the CVM-250 maraging steel is marginal at -275°F (fig. 7).

- FATIGUE CRACK GROWTH AND FRACTURE TOUGHNESS OF NITRONIC 40 TESTED AT -275°F.
- FRACTURE TOUGHNESS OF VASCOMAX 200 AND 250 MARAGING STEEL TESTED FROM ROOM TEMPERATURE TO -320°F.

Figure 1.- Objectives.

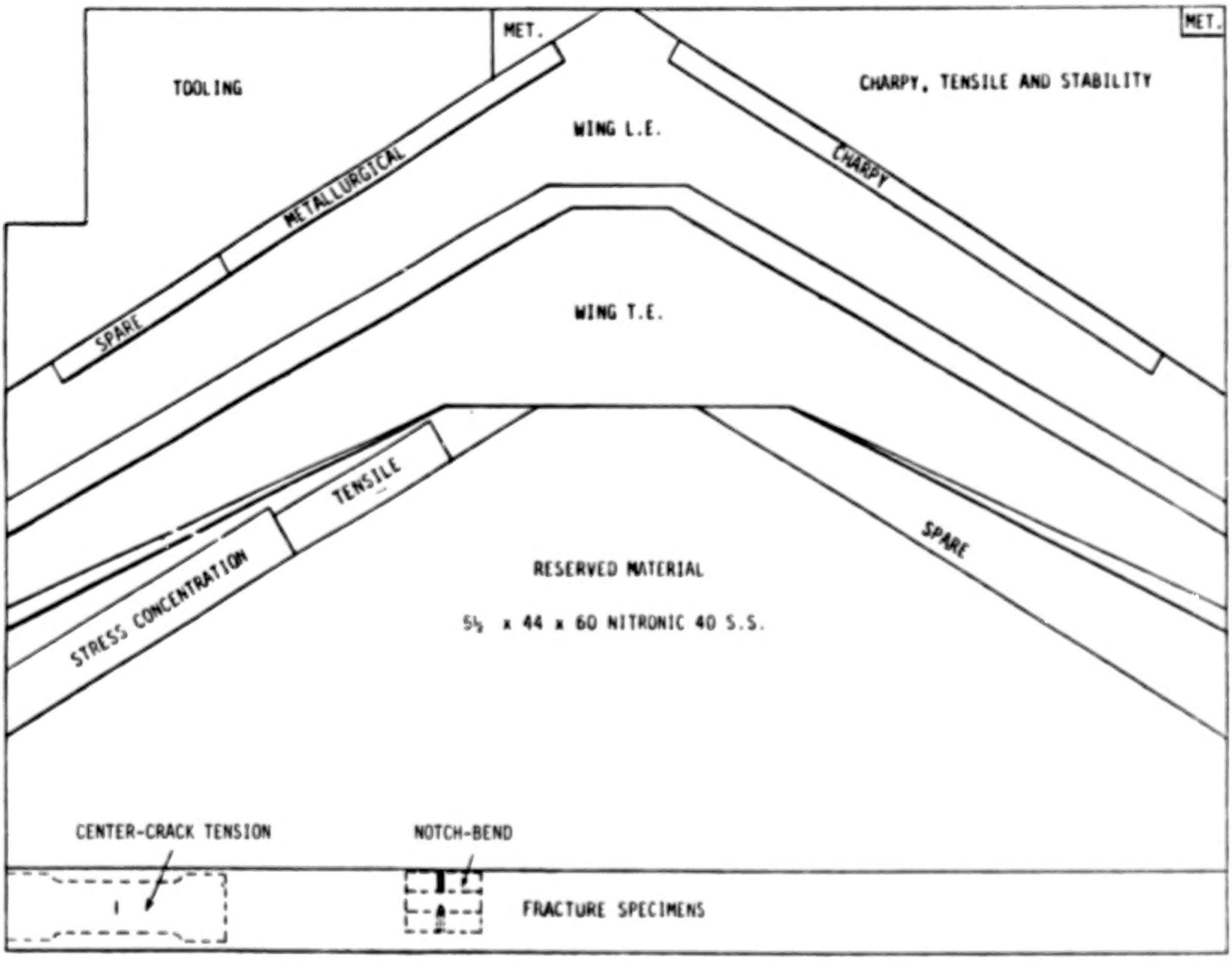
MET.
MET.
TOOLING
CHARPY, TENSILE AND STABILITY
WING L.E.
METALLURGICAL
CHARPY
SPARE
WING T.E.
TENSILE
STRESS CONCENTRATION
SPARE
RESERVED MATERIAL
5½ x 44 x 60 NITRONIC 40 S.S.
CENTER-CRACK TENSION
NOTCH-BEND
FRACTURE SPECIMENS

Figure 2.- NITRONIC 40 plate.

SPECIMENS	PURPOSE	CONDITION	NO. TESTED	HOLDOUTS
CENTER CRACK	TOUGHNESS	AS RECEIVED	3	(3 BLANKS)
		STRESS RELIEVED	3	4
NOTCH-BEND	FATIGUE - CRACK GROWTH AND TOUGHNESS	AS RECEIVED	9	(1 BLANK)
		STRESS RELIEVED	9	0

Figure 3.- NITRONIC 40 test specimens.

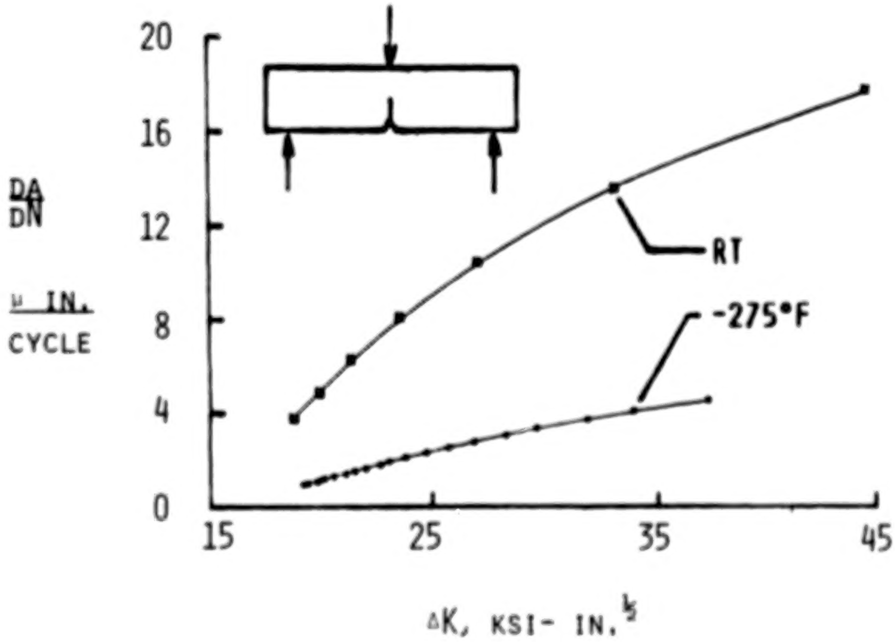

Figure 4.- Fatigue crack growth in NITRONIC 40 at two temperatures.

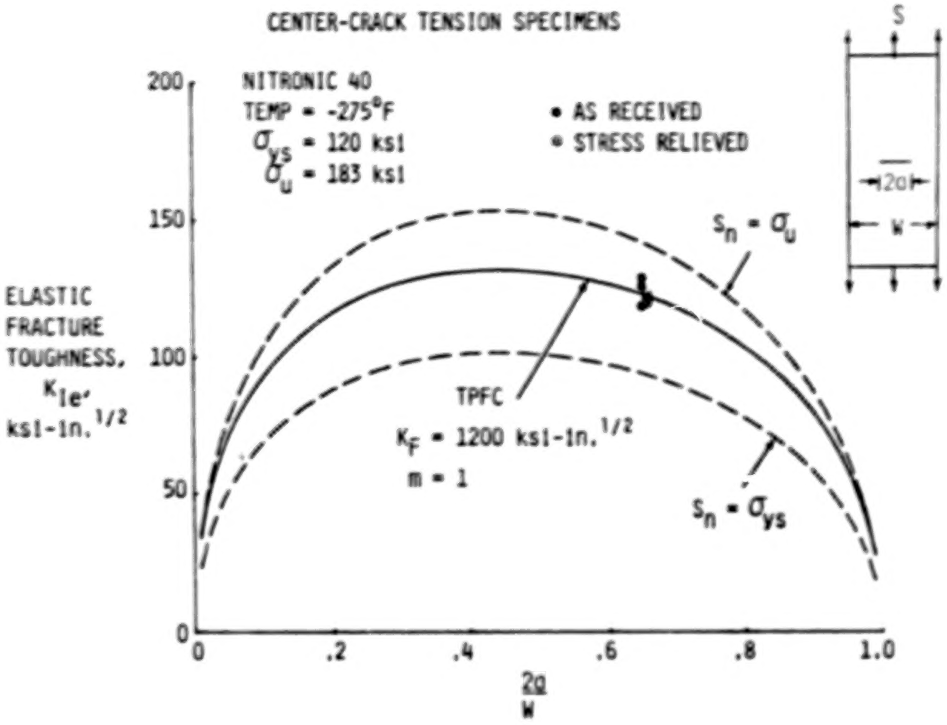

Figure 5.- Fracture toughness of NTF Pathfinder model material.

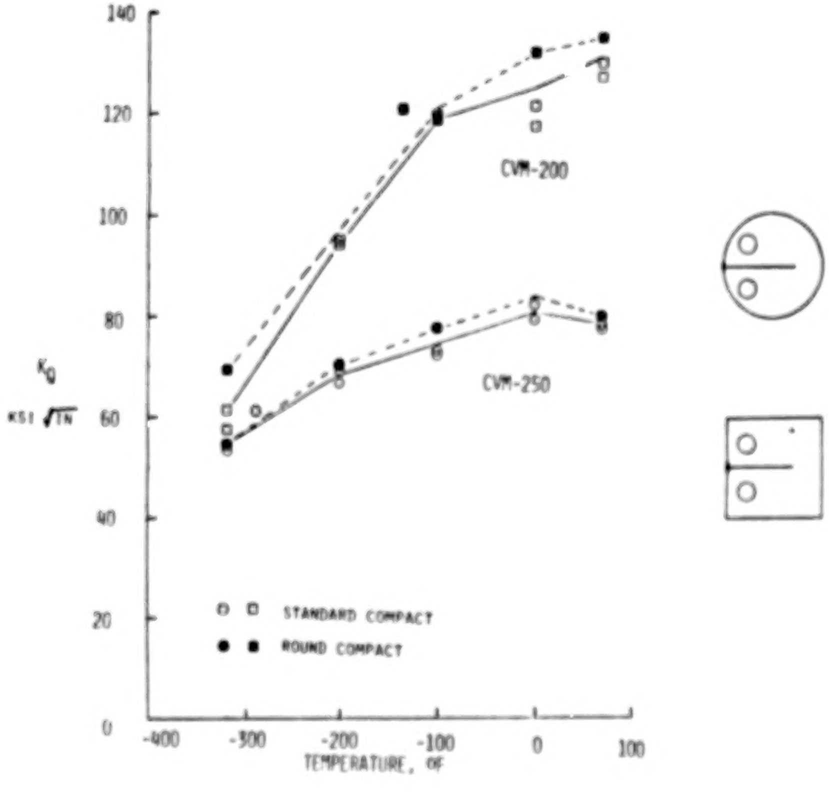

Figure 6.- Fracture toughness of two maraging steels.

- FRACTURE TOUGHNESS OF NITRONIC 40 MEETS PATHFINDER CRITERIA (85 KSI-IN.$^{1/2}$) AT CRYOGENIC TEMPERATURE (-275°F)

- CRACK INITIATION AND GROWTH IN NITRONIC 40 ARE MORE CRITICAL TO MODEL DESIGN THAN FRACTURE TOUGHNESS

- FRACTURE TOUGHNESS OF CVM-250 MARAGING STEEL DOES NOT MEET 85 KSI-IN.$^{1/2}$ CRITERIA AT ROOM TEMPERATURE AND CVM-200 MARAGING STEEL IS MARGINAL, BUT PROBABLY ACCEPTABLE, AT -275°F

Figure 7.- Conclusions.

ANALYTICAL METHODS WITH APPLICATION TO THE PATHFINDER I MODEL

William F. Hunter
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Hampton, Virginia

Introduction

The utilization of the high Reynolds number test capability provided by the National Transonic Facility (NTF) requires that models and stings designed and analyzed for operation in a cryogenic environment and in some cases at high dynamic pressures. The combination of high aerodynamic loads and strength limitations on cryogenically acceptable materials will necessitate that model/sting systems be designed to lower safety factors than those which have been used for conventional wind tunnel model/sting systems. This will necessitate that more rigorous and, in some cases, highly sophisticated analyses be performed along with math model verification tests. Also, proof testing may be required for critical applications.

Thermal Analysis

The importance of the thermal analysis for NTF models should not be underestimated. Because of the tunnel transients there will be thermal gradients in the various system components and temperature differences between mating parts. These effects must be evaluated since they can lead to high stresses or loose structural joints.

The cryogenic models will be subjected to various thermal transients. First, there is the initial cooldown period. Also, there will be changes in the tunnel test conditions. In order to make alterations to the models, the tunnel has been designed such that the model and a portion of the sting can be isolated from the cryogenic environment. This is done by enclosing the model in a moveable tube-like structure which passes across the test section. Before model changes can be made, the model must be heated. After model changes are made, the model will be subjected almost instantaneously to the cryogenic environment.

The effects of these transient conditions on the entire model, balance, and sting system must be examined. This means that several thermal math models may need to be developed in order to determine the time-dependent temperature distributions in the various parts. An evaluation of resulting gradients may show the existence of large thermal stresses.

The effects of thermal gradients and temperature changes on the structural joints in each system must be investigated. Since a loss of joint stiffness could lead to divergence or flutter problems, special attention should be given to the model-to-balance joint and to the balance-to-sting joint. For these and other joints, appreciable preloads may be needed in order to avoid joint looseness. When preloading, consideration should be given to both the positive and negative temperature swings so as to avoid over-stressing the joint.

The areas examined on the Pathfinder I model include the temperature distribution in the wing, the dowels in the wing which pass through the tongue and groove joint, the wing/strong back joint, the temperature distribution in the balance, the balance/sting joint, the sting/stub sting joint, the gradient in sting at the rear of the model, the heating requirements for the instrumentation package, and the temperature distribution along the fuselage surface in the region near the instrumentation package. The only design modifications resulting from the thermal analysis were (1) to increase the number and size of the dowels in the wing and (2) to change the eight wing/strong back shoulder bolts from a tight fit to a clearance fit and add two dowels.

Stress Analysis

In view of the potentially high aerodynamic loadings and large thermal gradients, a very thorough stress analysis is required for each model and sting system. The stresses in the various components of the system will probably be evaluated using both finite element and strength of material approaches. The thermal stresses will be studied using finite element models except in instances where the geometry and temperature distribution can be represented by a classical theory of elasticity problem whose solution is known.

Since many models will be designed with small safety factors, much emphasis must be given to stress concentrations. There are numerous reports and handbooks available for determining stress concentration factors. Also, if necessary, stress concentrations can be evaluated by making detailed finite element models of the highly stressed regions.

For the Pathfinder I model, the highest stress is due to the stress concentration around the orifice plugs in the wings. Other sources of stress concentrations are dowels or shear pins such as those incorporated in the Pathfinder I wing. Whenever possible, care should be taken to avoid placement of pins in highly stressed regions. Also, consideration should be given to designing pins to have slight interference fits since this can increase the fatigue life.

Development of Elastic Math Models

The aeroelastic and deformation analyses are dependent upon the development of accurate elastic math models of the model and sting system. For the Pathfinder I model, two different types of math models were used in the analysis: one is a beam representation of the wing and the other is a finite element approach.

It is believed that many high aspect ratio wings such as those of Pathfinder I can be analyzed by treating the wing as a beam. The deformations (bending in two planes, torsion, and extension) are described by twelve first-order differential equations. The static and natural vibration solutions to the equations are obtained using a transfer matrix approach that is based upon Runge-Kutta integration.

The beam approach is a quick and efficient method for calculating stresses, deflections, and frequencies. The solution method easily handles any discontinuities in the cross-sectional properties. Also, the formulation conveniently accommodates displacement-dependent loads as well as direct loads.

A beam math model was used to predict the deformations and stresses for the Pathfinder I wing.

Two finite element models have been developed for analyzing Pathfinder I. One is a detailed model of the wing by itself and the other is a model of the system.

A SPAR model of the wing alone was developed using solid finite elements. SPAR is a general purpose finite element computer program for performing structural and thermal analyses. This model is made up of about 600 elements.

The SPAR program was chosen for modeling the Pathfinder I model/balance/sting system since it is compatible with some of the flutter codes available at the Langley Research Center. The wing was modeled using plate elements. The stiffness and mass properties of the fuselage, balance, and sting were represented by beam elements. The sting was assumed cantilevered at the strut.

The natural frequencies of this plate model wing by itself have been computed. It was found that for the first three nodes, the calculated frequencies agreed within 8 percent with the measured frequencies of a supercritical test wing which is nearly identical to the Pathfinder I wing.

The PATRAN-G computer program, which has been recently leased by the Langley Research Center, appears to be a very useful tool for analyzing wind tunnel models. The program is an expedient method for generating structural finite element models. From an interactive terminal, the user of the program generates a geometric model of the structure. Then, by using the appropriate translator, the finite element model is automatically generated from the geometric model. Translators are currently available for the NASTRAN and EAL finite element programs. The PATRAN-G program was recently used to develop a finite element model of the Pathfinder I wing.

Verification Testing

It is important that the elastic math models used in the analyses be verified by testing of the actual hardware. This is especially true if the design is marginal. The math models can be confirmed by performing load/displacement tests, measuring natural frequencies, and using strain gage data. Also, joint effects, which are often unpredictable, can be evaluated by testing.

Load/displacement tests have been conducted on supercritical wings which are very similar to the Pathfinder I wings. The test wings have the same airfoil shape and the same planform as the Pathfinder I wings. One of the test wings has a solid cross section and the other has a tongue and groove joint similar to that of the Pathfinder I design. The only significant structural difference between the Pathfinder I wing and the supercritical test wing having the tongue and groove joint is that the Pathfinder I wing is continuous from tip to tip, whereas the test wing is a semi-span wing. The testing of both the solid and the tongue and groove wings was not only beneficial for obtaining data for comparing with calculated results, but showed the effects of the tongue and groove joint on the bending and torsional stiffnesses and on the natural vibration characteristics.

The bending displacements were measured with a machine that is normally used for measuring and checking the coordinates of models. The load was applied using a screw jack and load cell arrangement with the load being monitored with a digital readout. Each wing was bolted to the fixture in the same manner that it is fastened to its fuselage. The wings were loaded at seven equally spaced points along the elastic axis. For each point load, the displacements were measured at a large number of points on the wing's surface. The coordinate measurements made before, during, and after each loading were recorded on punch cards for later data processing.

With the wing mounted to the same fixture, torsional load/displacement tests were also made. The torque was applied through a device which was clamped to the airfoil.

The calculated bending displacements were found to agree very well with the measurements for all seven of the loading conditions. However, the torsional tests indicated that the torsional stiffness of the tongue and groove test wing is only about one-half of that calculated from the cross-sectional data. This stiffness reduction can definitely be attributed to the tongue and groove joint since the tests conducted on the solid wing showed very good agreement between the measured and calculated torsional displacements.

Deformation Analysis

The deformation analysis is essential to the design of highly loaded models. Because of the large deformations, many models will be built with a jig shape such that the model lifting surfaces will have the proper shape when loaded. Thus, it is necessary to be able to predict accurately the deflections of wings under aerodynamic loads. After the beam math model was verified by the load/displacement tests discussed above, the jig shape for the Pathfinder I model was computed for the cruise condition loads ($C_L = 0.555$ and $q = 2800$ psf).

Aeroelastic Analyses

The aeroelastic analyses require the development of a math model of the entire model, balance, and sting system. The aeroelastic analyses consist of determining the natural vibration modes, using these modes as displacement functions in the flutter and divergence studies, and performing any needed dynamic response analyses.

It is thought that the flutter analysis, as well as the divergence analysis, must treat the entire system. As might be expected, vibration tests at Langley Research Center have shown appreciable differences in the modes and frequencies of the aforementioned supercritical wing mounted on and off the balance/sting support. These differences reflect the influence of balance/sting flexibility effects on the system model characteristics. Also, since aeroelastic divergence and flutter are of great concern for models that may be tested at high dynamic pressures in the NTF, the analyses must give particular attention to the stiffness of structural joints.

There are various computer codes available at Langley for performing flutter analyses. A system of programs called FAST (flutter analysis system) was used in the analysis of the Pathfinder I model. The unsteady aerodynamics programs in FAST are based on the subsonic kernel function lifting-surface theory.

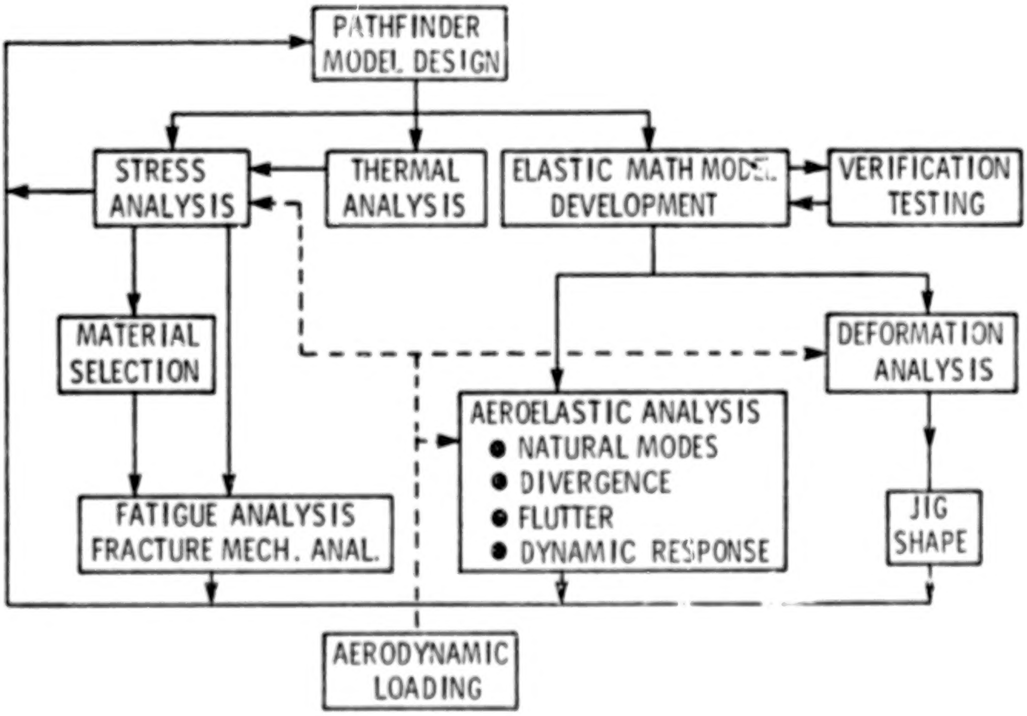
Integrated Computer Program

It is planned that the various elements of the analysis discussed above will eventually be combined into an integrated computer program. Such a program is needed for efficient and systematic evaluation of model/sting systems for the NTF.

REQUIRED ANALYSES

- AERODYNAMIC LOADS
- THERMAL ANALYSIS
- STRESS ANALYSIS
- FATIGUE ANALYSIS
- FRACTURE MECHANICS ANALYSIS
- DEFORMATION ANALYSIS
- VIBRATION ANALYSIS
- FLUTTER ANALYSIS
- DIVERGENCE ANALYSIS

DESIGN BY ANALYSIS FLOW DIAGRAM


PATHFINDER MODEL DESIGN
STRESS ANALYSIS
THERMAL ANALYSIS
ELASTIC MATH MODEL DEVELOPMENT
VERIFICATION TESTING
MATERIAL SELECTION
DEFORMATION ANALYSIS
AEROELASTIC ANALYSIS
● NATURAL MODES
● DIVERGENCE
● FLUTTER
● DYNAMIC RESPONSE
FATIGUE ANALYSIS FRACTURE MECH. ANAL.
JIG SHAPE
AERODYNAMIC LOADING

COMPUTER PROGRAMS BEING USED FOR ANALYZING CRYO MODELS

- EAL/SPAR
  - DEFORMATION ANALYSIS
  - STRESS ANALYSIS
  - NATURAL VIBRATION CHARACTERISTICS
  - THERMAL ANALYSIS
- FAST
  - FLUTTER ANALYSIS
  - DIVERGENCE ANALYSIS
- STING DIVERGENCE PROGRAM
- STING DEFORMATION PROGRAM
- SPECIAL PROGRAMS FOR HIGH ASPECT RATIO WINGS
  - CROSS-SECTIONAL PROPERTIES PROGRAM
  - DISTRIBUTED AERODYNAMIC LOADS PROGRAM
  - WING DEFORMATION PROGRAM
  - WING STRESS PROGRAM
- FRACTURE MECHANICS PROGRAMS

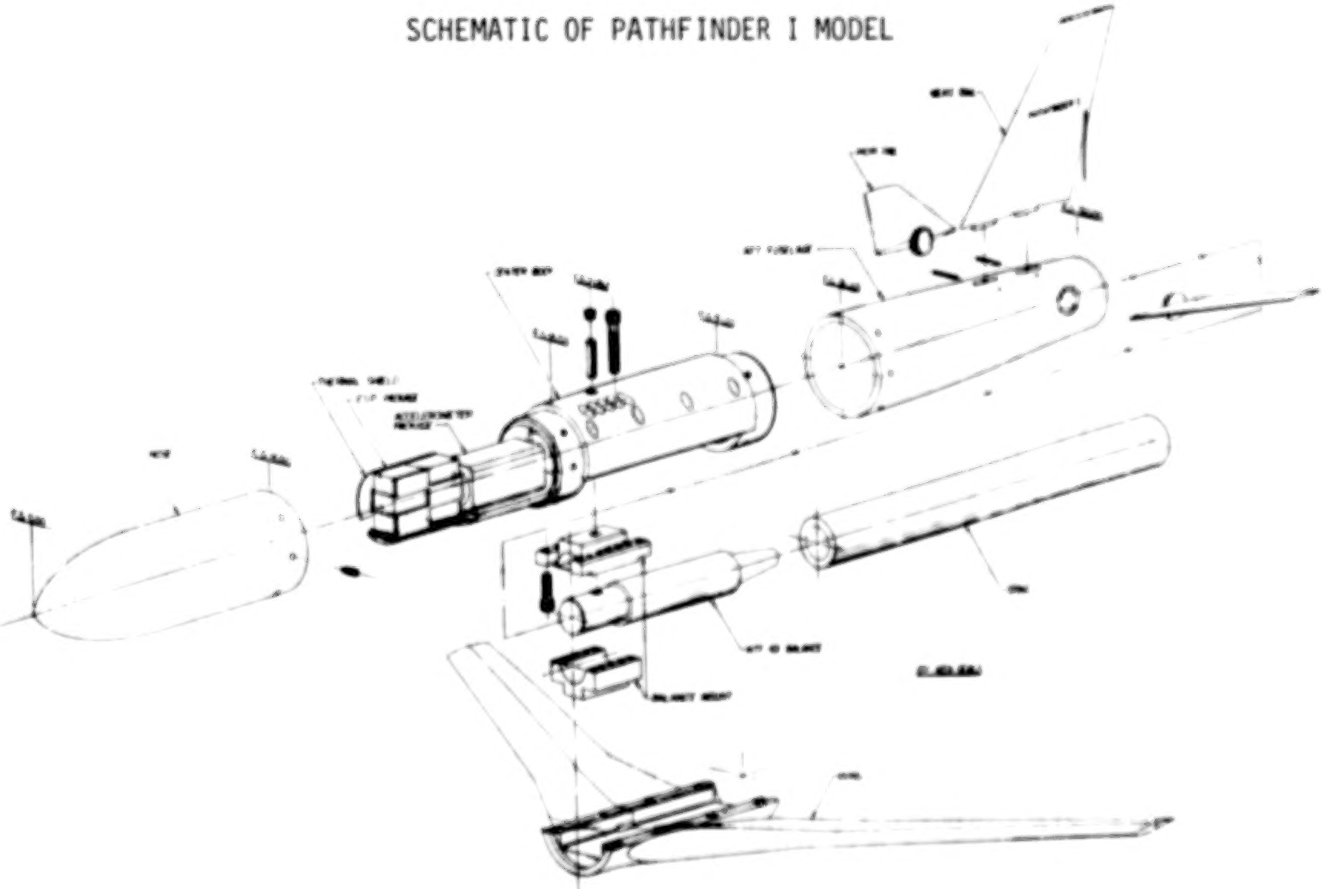
OTHER AVAILABLE COMPUTER PROGRAMS FOR ANALYZING CRYO MODELS

- PATRAN-G (FEM GENERATOR)
- NASTRAN
  - STRESS ANALYSIS
  - DEFORMATION ANALYSIS
  - NATURAL VIBRATION CHARACTERISTICS
  - THERMAL ANALYSIS
  - FLUTTER ANALYSIS
- MITAS (THERMAL ANALYSIS)

THERMAL ANALYSES

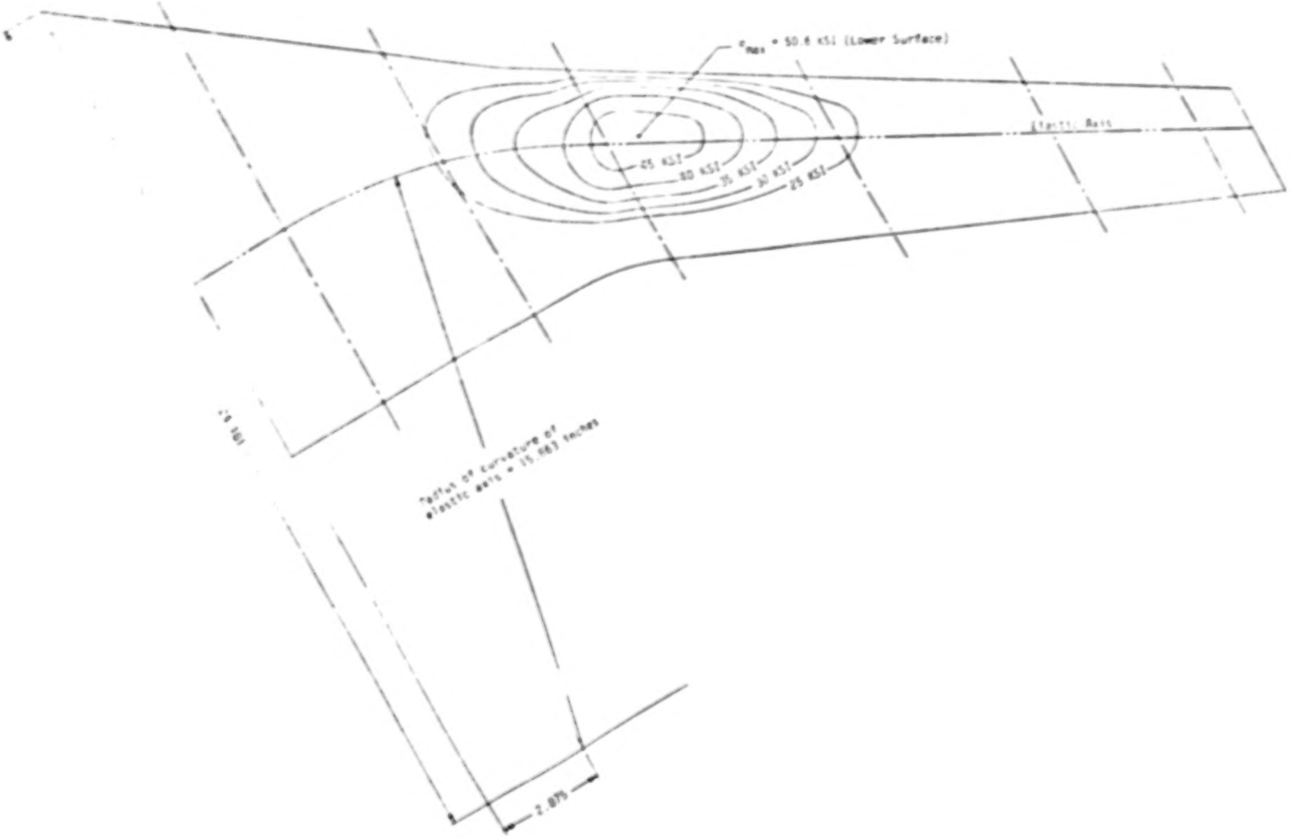
- SOURCES OF TRANSIENT CONDITIONS
  - INITIAL COOLDOWN
  - CHANGE IN TUNNEL TEST CONDITIONS
  - BEFORE AND AFTER MODEL CHANGES
- AREAS TO BE INVESTIGATED
  - THERMAL GRADIENTS
  - TEMPERATURE DIFFERENCE OF MATING PARTS
  - INSULATION OF INSTRUMENTATION PACKAGE
  - TIME TO REACH THERMAL EQUILIBRIUM

SCHEMATIC OF PATHFINDER I MODEL

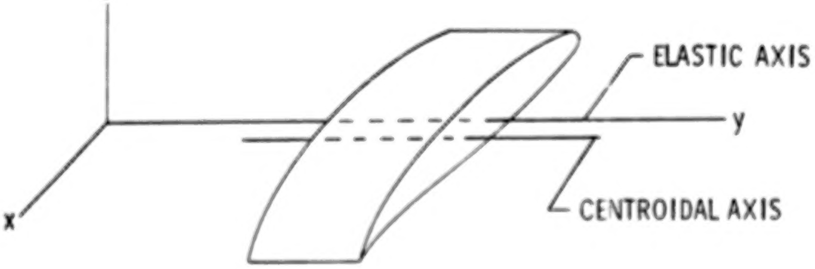


BEST DOCUMENT AVAILABLE

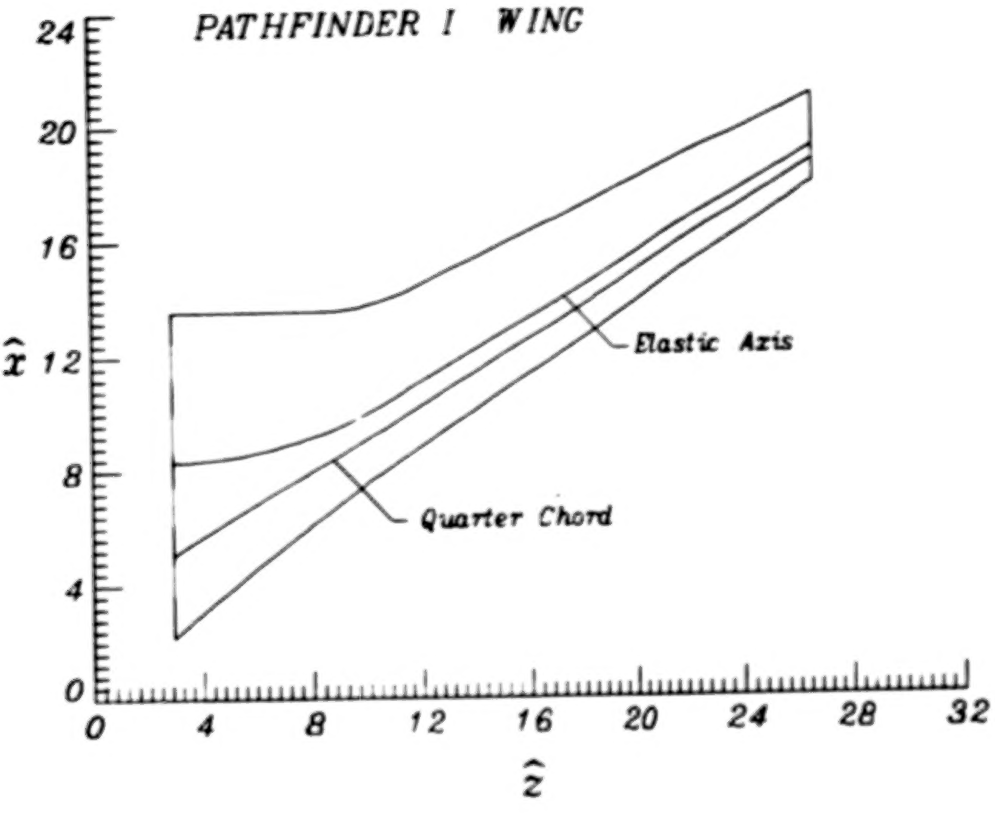
BENDING STRESS DISTRIBUTION
FOR $C_L = 1.0$, $Q = 2800$ PSF


σmax = 50.6 KSI (Lower Surface)
45 KSI
40 KSI
35 KSI
30 KSI
25 KSI
Elastic Axis
Radius of curvature of elastic axis = 15.863 inches
20.101
2.075

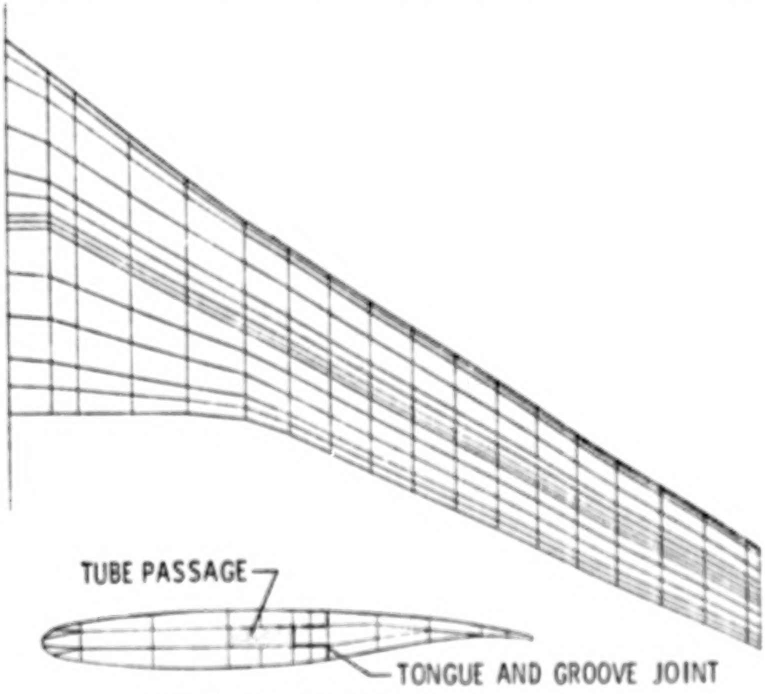
BEAM MODEL OF WING


z
x
y
ELASTIC AXIS
CENTROIDAL AXIS

ASSUMPTIONS	FEATURES
• TWISTED CANTILEVERED BEAM	• QUICK AND EFFICIENT
• UNSYMMETRICAL CROSS-SECTION	• HANDLES STRUCTURAL DISCONTINUITIES
• BENDING IN TWO PLANES, TORSION, EXTENSION	• HANDLES DISPLACEMENT DEPENDENT LOADS
	• STREAMWISE AERODYNAMICS ON SWEPT WING

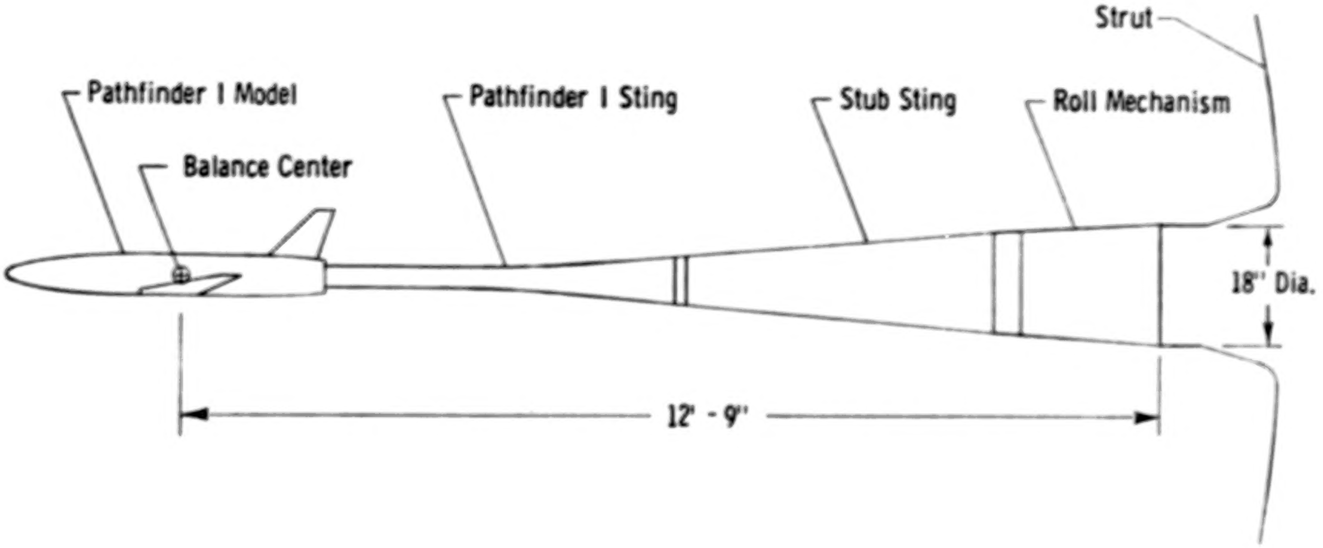


SPAR FINITE ELEMENT MODEL PATHFINDER I WING

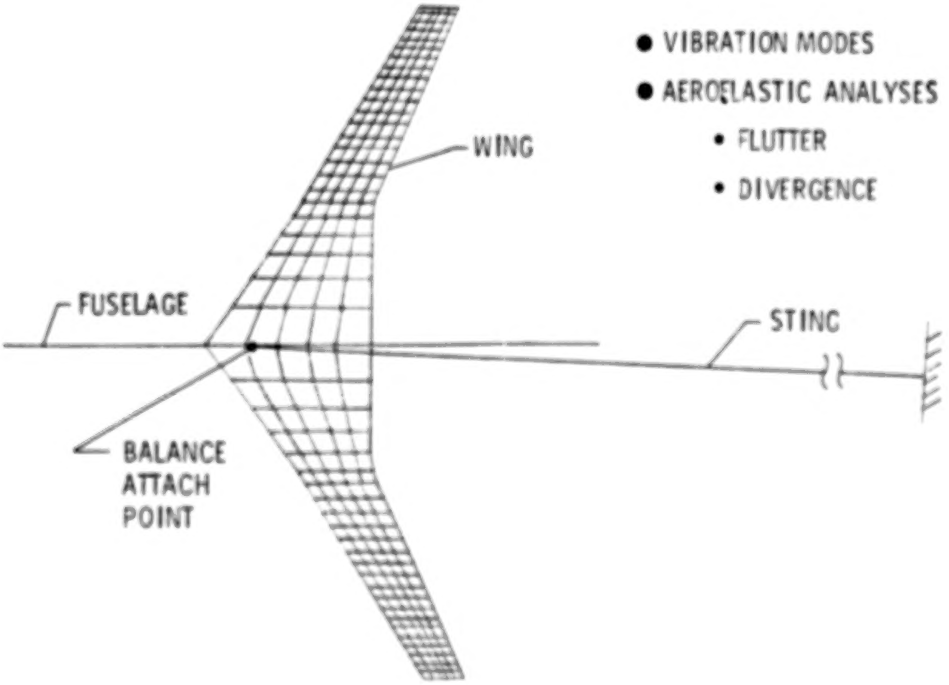

TUBE PASSAGE
TONGUE AND GROOVE JOINT

TYPICAL CROSS SECTION

PATHFINDER I STING CONFIGURATION


Strut
Pathfinder I Model
Pathfinder I Sting
Stub Sting
Roll Mechanism
Balance Center
18'' Dia.
12' - 9''

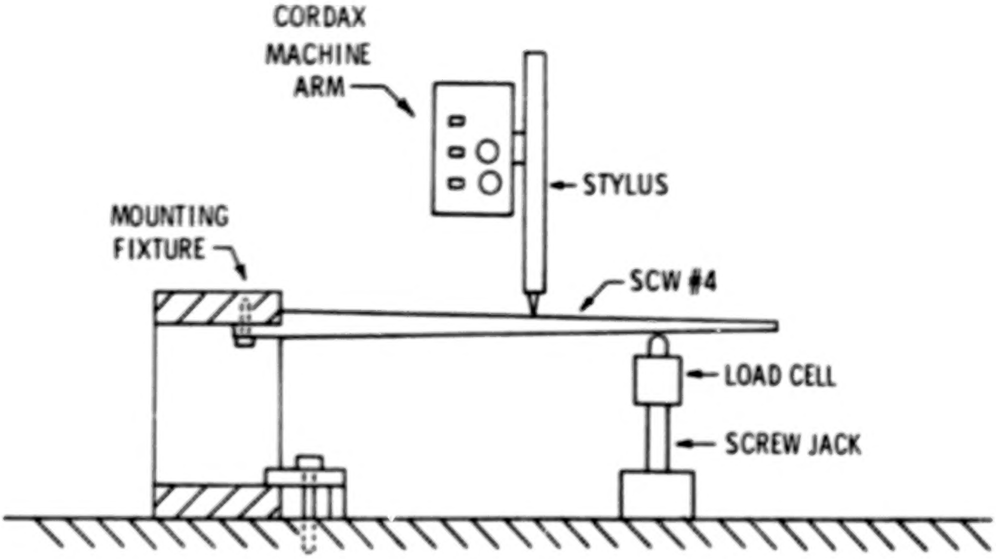
AEROELASTIC FINITE ELEMENT MODEL OF PATHFINDER I


WING
FUSELAGE
STING
BALANCE
ATTACH
POINT

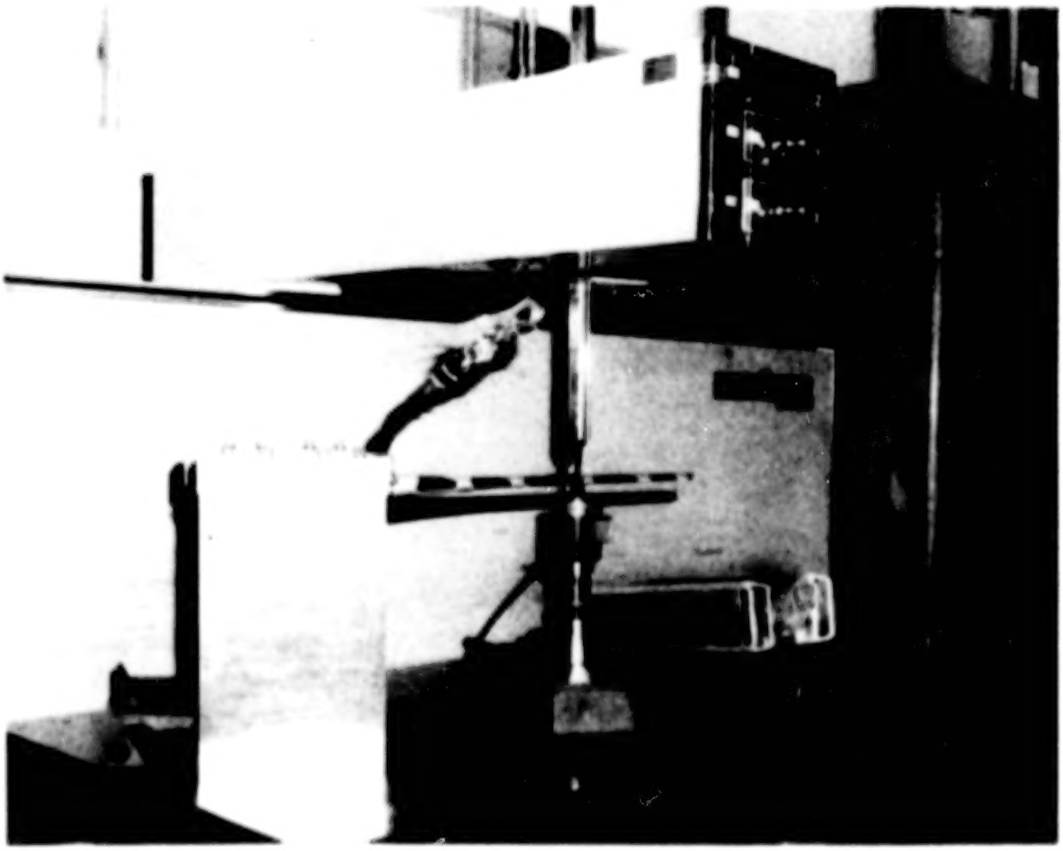
- ● VIBRATION MODES
- ● AEROELASTIC ANALYSES
  - • FLUTTER
  - • DIVERGENCE

BEST DOCUMENT AVAILABLE

SCHEMATIC OF SUPERCRITICAL WING LOAD/DISPLACEMENT MEASUREMENTS


CORDAX MACHINE ARM
STYLUS
MOUNTING FIXTURE
SCW #4
LOAD CELL
SCREW JACK

SUPERCRITICAL WING LOAD/DISPLACEMENT MEASUREMENTS



COMPARISON OF MEASURED AND COMPUTED BENDING DISPLACEMENTS FOR SCW#4 (INSTRUMENTED WING)

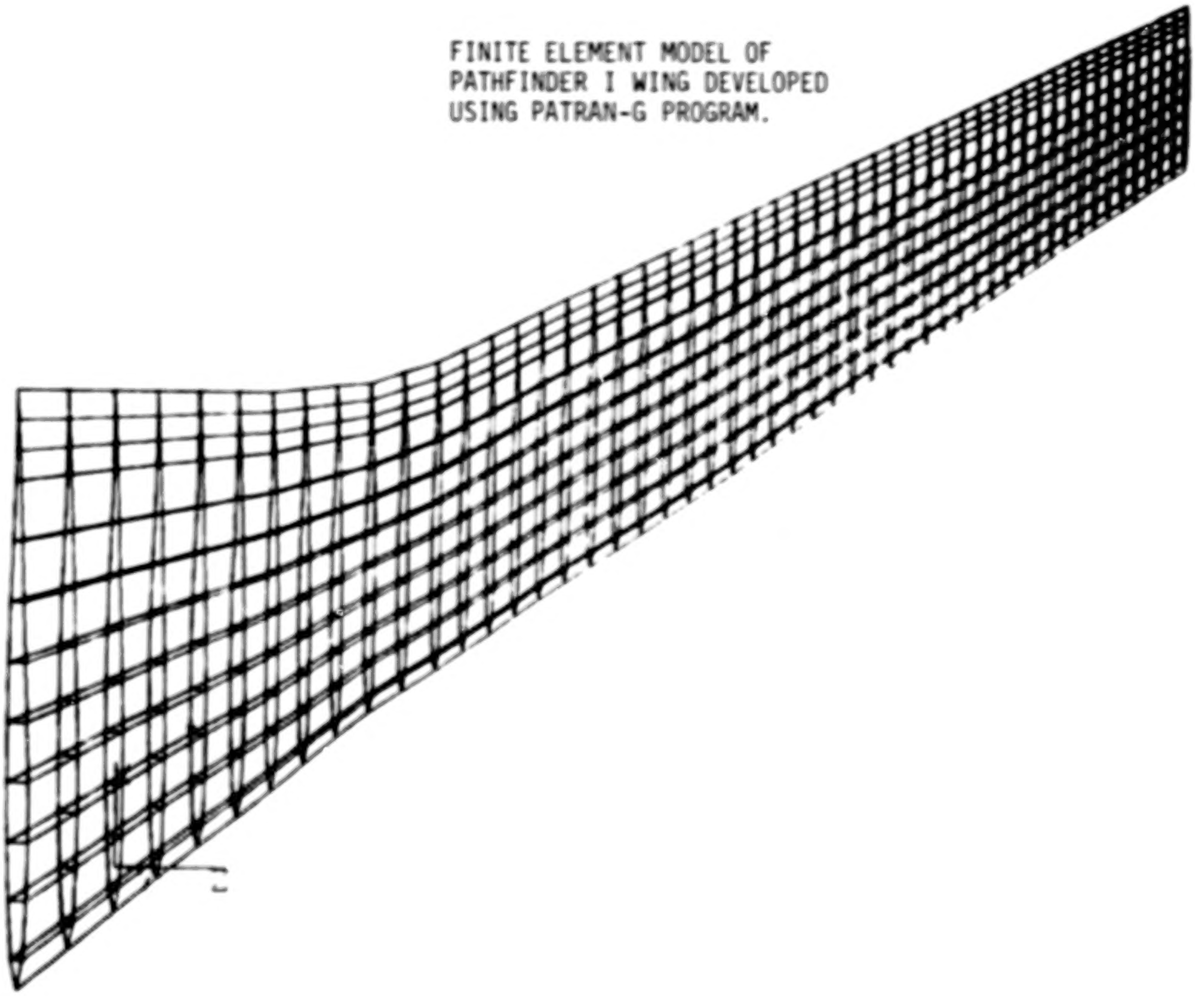
z, in.	Displacement, in., for 100 lb at $z = 30$ in.		Displacement, in., for 150 lb at $z = 27$ in.		Displacement, in., for 200 lb at $z = 24$ in.		Displacement, in., for 250 lb at $z = 21$ in.	
	Measured	Computed	Measured	Computed	Measured	Computed	Measured	Computed
6.0	0.004	0.004	0.005	0.005	0.006	0.006	0.007	0.006
9.0	.009	.009	.011	.011	.013	.013	.014	.014
12.0	.017	.017	.022	.022	.025	.025	.027	.027
15.0	.033	.032	.042	.042	.047	.047	.049	.048
18.0	.061	.059	.076	.076	.084	.084	.083	.081
21.0	.101	.100	.125	.124	.133	.132	.125	.122
24.0	.155	.154	.187	.186	.191	.189	.167	.165
27.0	.223	.221	.258	.258	.249	.248	.209	.207
30.0	.303	.302	.331	.332	.307	.307	.251	.250

z, in.	Displacement, in., for 400 lb at $z = 18$ in.		Displacement, in., for 500 lb at $z = 15$ in.		Displacement, in., for 500 lb at $z = 12$ in.	
	Measured	Computed	Measured	Computed	Measured	Computed
6.0	0.009	0.008	0.009	0.008	0.007	0.006
9.0	.019	.019	.018	.018	.014	.013
12.0	.034	.034	.033	.033	.023	.023
15.0	.060	.059	.053	.053	.033	033
18.0	.094	.094	.074	.074	.043	.043
21.0	.130	.130	.095	.096	.053	.053
24.0	.166	.165	.115	.117	.063	.063
27.0	.201	.201	.135	.139	.072	.073
30.0	.236	.237	.155	.160	.082	.083

DEFORMATIONS FOR CRUISE CONDITION LOADINGS: $C_L = 0.555$, $Q = 2800$ PSF

TIP DISPLACEMENT = 0.594 INCHES

TIP ROTATION = 1.191 DEGREES
(Leading Edge Down)



FINITE ELEMENT MODEL OF
PATHFINDER I WING DEVELOPED
USING PATRAN-G PROGRAM.

SUMMARY

- PATHFINDER I ANALYSIS
    - STRESS - BEAM THEORY
    - DEFORMATION - BEAM THEORY
    - THERMAL - SPAR
    - VIBRATION - SPAR
    - FLUTTER - FAST
    - DIVERGENCE - SPECIAL PROGRAM
- CONTINUING DEVELOPMENT AND INVESTIGATION OF OTHER ANALYTICAL TOOLS. COMPUTER PROGRAMS TO BE DOCUMENTED.
- GOAL IS TO DEVELOP AN INTEGRATED COMPUTER PROGRAM FOR ANALYZING WIND TUNNEL MODELS.

STATUS OF NTF MODELS

James F. Bradshaw
NASA Langley Research Center
Hampton, Virginia

Langley Research Center has eight (8) research models currently being designed and fabricated that will be tested in the National Transonic Facility. These models are:

1. NTF Pathfinder I Model (PFI)
   This model is a wide body transport configuration with a high aspect ratio supercritical airfoil shape wing. It is designed to be tested in any configuration from fuselage only to a model including fuselage, wing and empennage. Three wings have been designed to be tested on this model. They are:

   a. Instrumented Wing (PFI) - This wing is the basic wing for the PFI model. It is constructed to a "jig shape" that produces the correct aerodynamic configuration when tested at a q of 2800 psf and a C_L of .55. The wing is instrumented with pressure orifices, thermocouples, and buffet gages.

   b. Solid Wing (PFL-1) - This wing has the same "jig shape" and planform as the PFI wing.

   c. Controls Wing (PFI-2) - This wing is similar to the other wings except it is not constructed to a "jig shape" and it will have trailing edge flaps and ailerons.

   The model fuselage, empennage and instrumented wing (PFI) material is NITRONIC 40 stainless steel. The solid wing (PFI-1) material is PH 13-8 Mo stainless steel in the 1150 M heat treatment condition. The controls wing (PFI-2) material is Vascomax 200 steel.

   The PFI-1 configuration (fuselage, empennage, and solid wing) is complete. The instrumented wing (PFI) will be completed in April 1983. The he controls wing (PFI-2) is scheduled to be completed in October 1983.

2. 1/2 Scale Pathfinder I Model
   This is a 1/2 size model of the PFI-1 configuration. It will be tested to provide tunnel wall interference data. All parts of this model will be constructed from PH 13-8 Mo stainless steel heat treated to the H1150 M condition.

   The model is scheduled to be completed in May 1983.

3. Calibration Bodies
   These consist of six (6) bodies of revolution having the same shape and size as models tested in other LRC wind tunnels. These models are in the design phase and will be constructed from 6061 aluminum alloy with a steel balance mount. The completion date for all size models is mid-May 1983.

4. Pathfinder II Model (PFII)
   The PFII is a model of a high performance aircraft configuration. The basic model configuration consist of an area ruled fuselage, highly cambered and twisted wing, vertical tail and adjustable horizontal tails. The fuselage will have a joint forward of the wing to allow for mounting a nose section with strakes (an alternate configuration) on a force measuring balance. Also the fuselage will be designed so the canopy can

be reshaped to adjust the model area distribution for alternate wings. The basic wing will have pressure orifices.

The model material will be Vascomax 200. The schedule for this model is to complete the design in April 1983 and the fabrication in October 1983.

5. Shuttle Orbiter Model
This is a .02 scale model of the Space Shuttle Orbiter vehicle. It will have remotely controlled elevons and rudder/speed brake. The elevons will be actuated by a DC motor-screw drive system thru ±20° angle. The rudder/speed brake will be actuated by a similar drive system to 0°, 15°, 25°, 40°, 55°, 70° and 87.2° included angles between speed brake surfaces. The model material is AMS 5737 H stainless steel (A286). The fabrication completion date is September 1983.

6. SCR Model
The SCR model is a .025 scale model of a representative supersonic cruise research configuration. The model will have leading edge flaps. Vascomax 200 steel has been selected as the model material. This model is currently in the design stage and the fabrication is scheduled to be completed in September 1983.

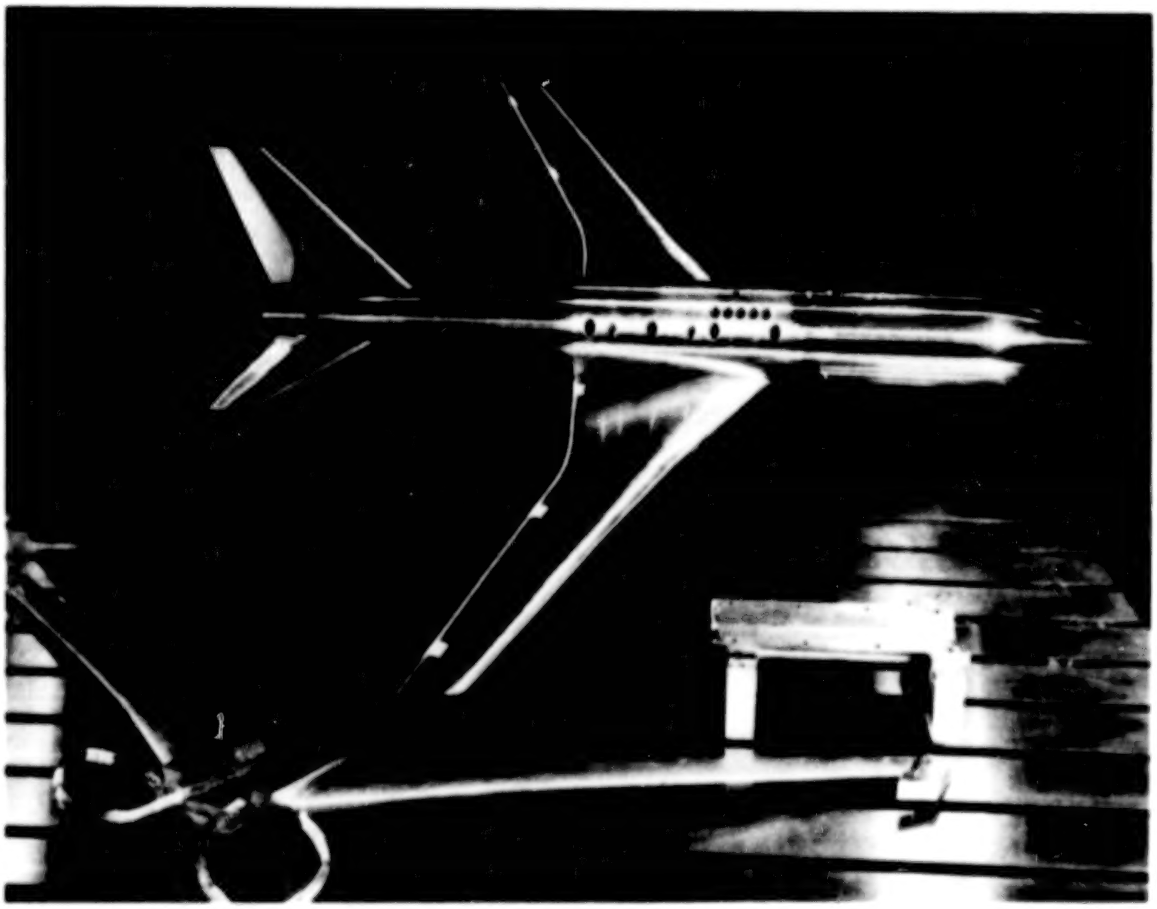
7. Delta Wing Model
The delta wing model is a flat plate with removable leading edges. The wing and leading edges will be pressure instrumented. The model material is Vascomax 200 steel and the completion date is September 1983.

8. LANN Wing
The LANN Wing is an existing semi-span wing. Although the wing material is NITRONIC 40 stainless steel, it will have to be completely refurbished; i.e., all carbon steel screws and dowels, as well as the instrumentation, will have to be replaced to make it acceptable for testing at cryogenic temperatures. The completion date for this work is late 1984.

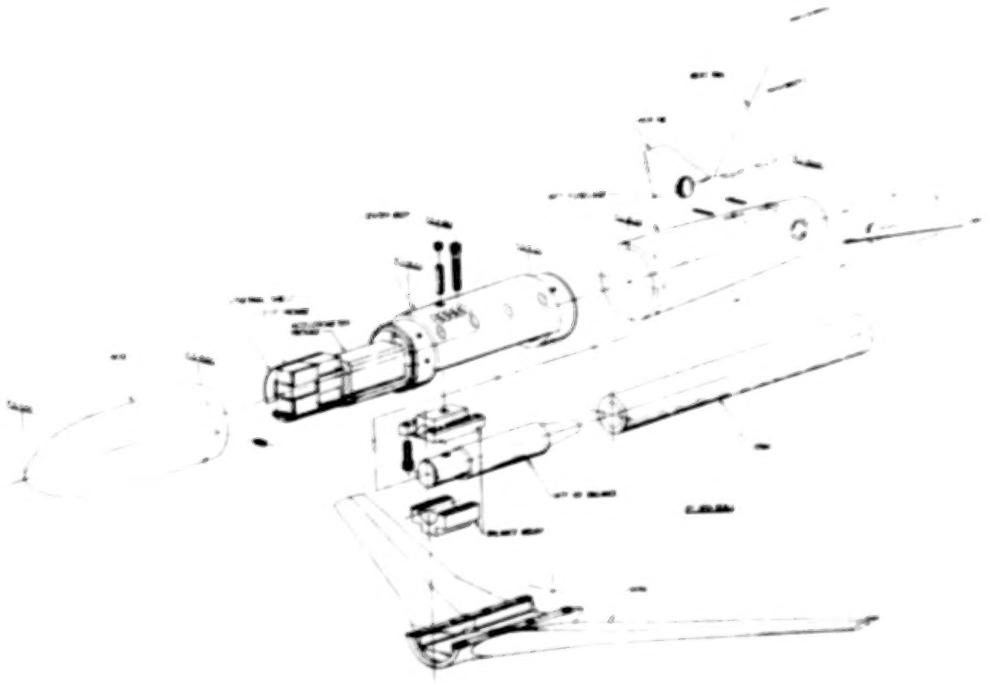
NTF MODELS

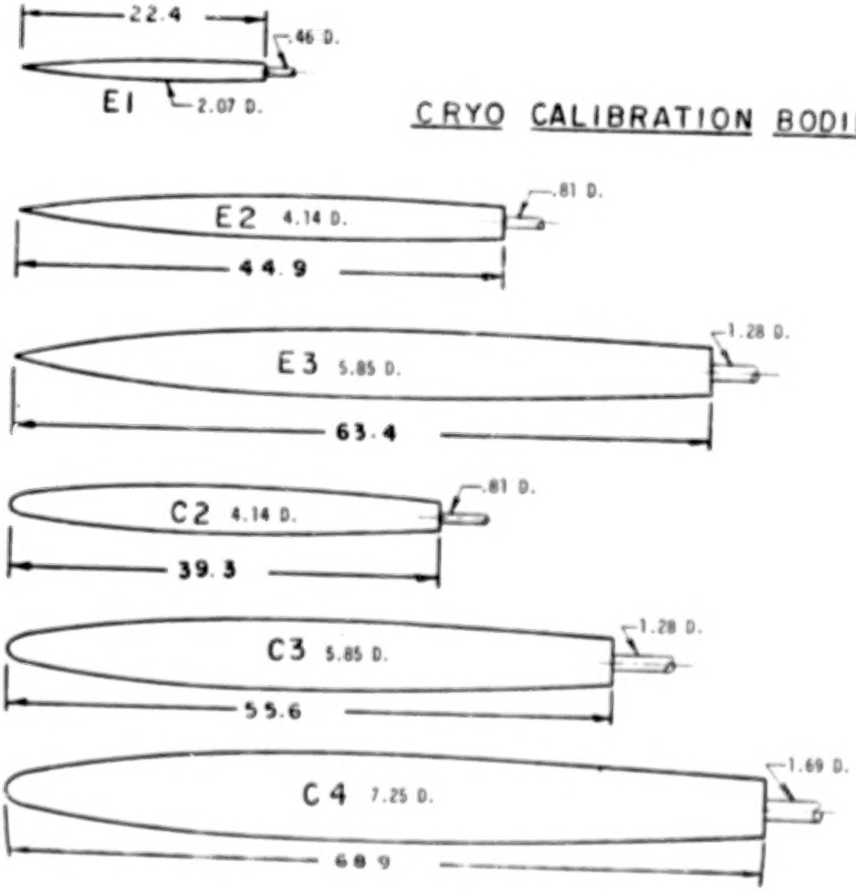
MODEL	INSTRUMENTATION	MATERIAL	STATUS
PATHFINDER I			
A INSTRUMENTED WING	PRESSURE AND FORCE	NITRONIC 40	FAB
B SOLID WING	FORCE	PH 13-8MO	COMP
C CONTROLS WING	FORCE	VASCOMAX 200	DESIGN
1/2 SCALE PATHFINDER I	FORCE	PH 13-8MO	FAB
CALIBRATION BODIES	PRESSURE AND FORCE	6061 ALUMINUM	DESIGN
PATHFINDER II	PRESSURE AND FORCE	VASCOMAX 200	DESIGN
SHUTTLE ORBITER	PRESSURE AND FORCE	A 286	DESIGN
SCR	PRESSURE AND FORCE	VASCOMAX 200	DESIGN
DELTA WING	PRESSURE AND FORCE	VASCOMAX 200	DESIGN
LANN WING	STATIC AND DYNAMIC PRESSURE	NITRONIC 40	EXISTING

PATHFINDER I MODEL



SCHEMATIC OF PATHFINDER I MODEL



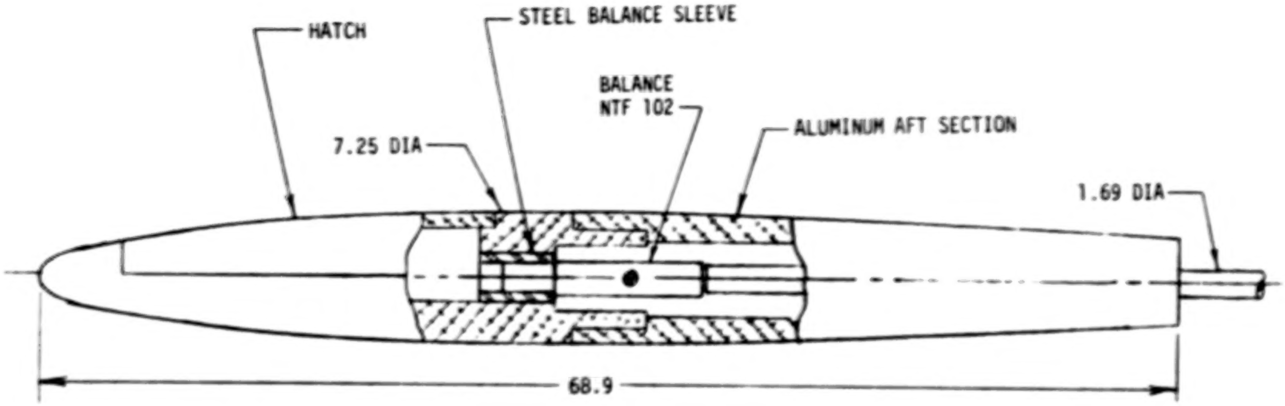


CRYO CALIBRATION BODIES

22.4
.46 D.
E1
2.07 D.
.81 D.
E2 4.14 D.
44.9
1.28 D.
E3 5.85 D.
63.4
.81 D.
C2 4.14 D.
39.3
1.28 D.
C3 5.85 D.
55.6
1.69 D.
C4 7.25 D.
68.9

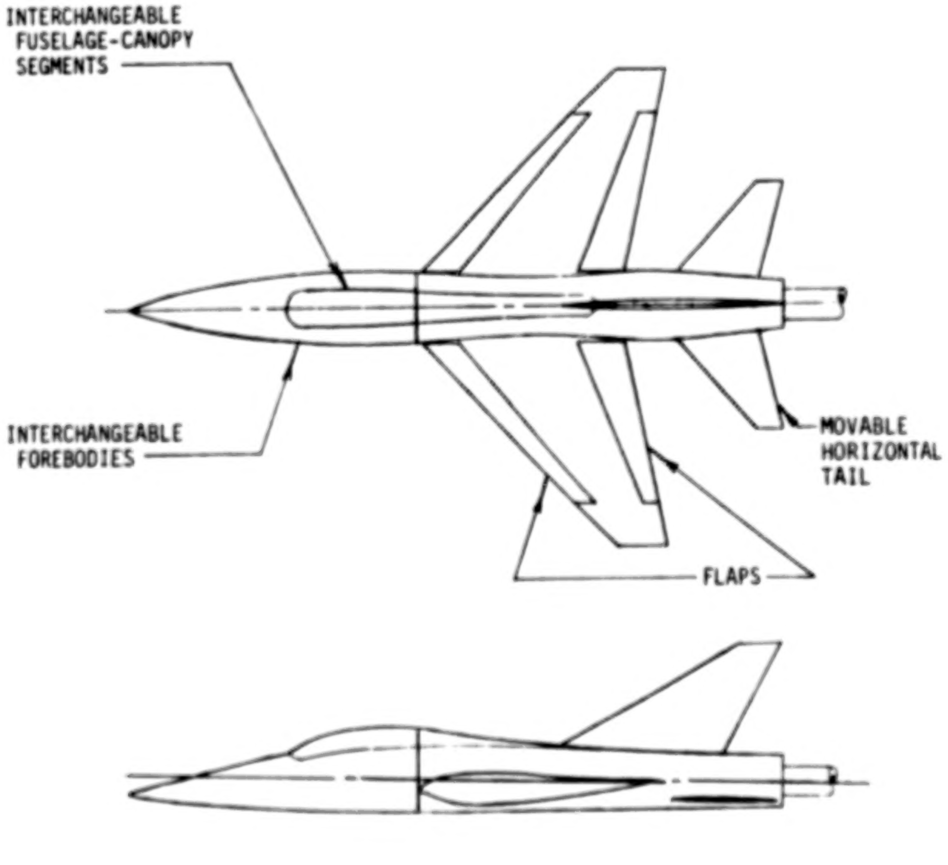
BEST DOCUMENT AVAILABLE

C4 CALIBRATION BODY

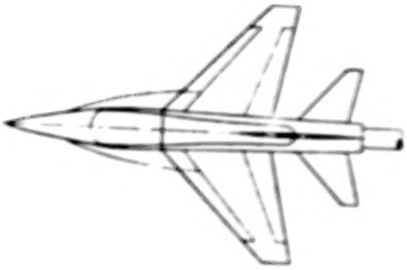

HATCH
STEEL BALANCE SLEEVE
BALANCE
NTF 102
ALUMINUM AFT SECTION
7.25 DIA
1.69 DIA
68.9

PATHFINDER II

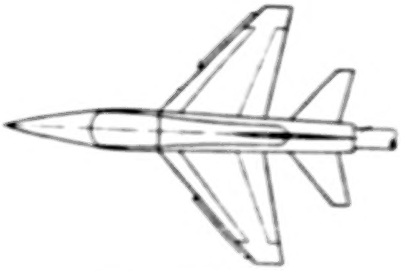
LENGTH 38.0" SPAN 26.7"
M_∞ 0.95, Q 1309 #/FT^2


INTERCHANGEABLE
FUSELAGE-CANOPY
SEGMENTS
INTERCHANGEABLE
FOREBODIES
MOVABLE
HORIZONTAL
TAIL
FLAPS

PATHFINDER II VARIATIONS

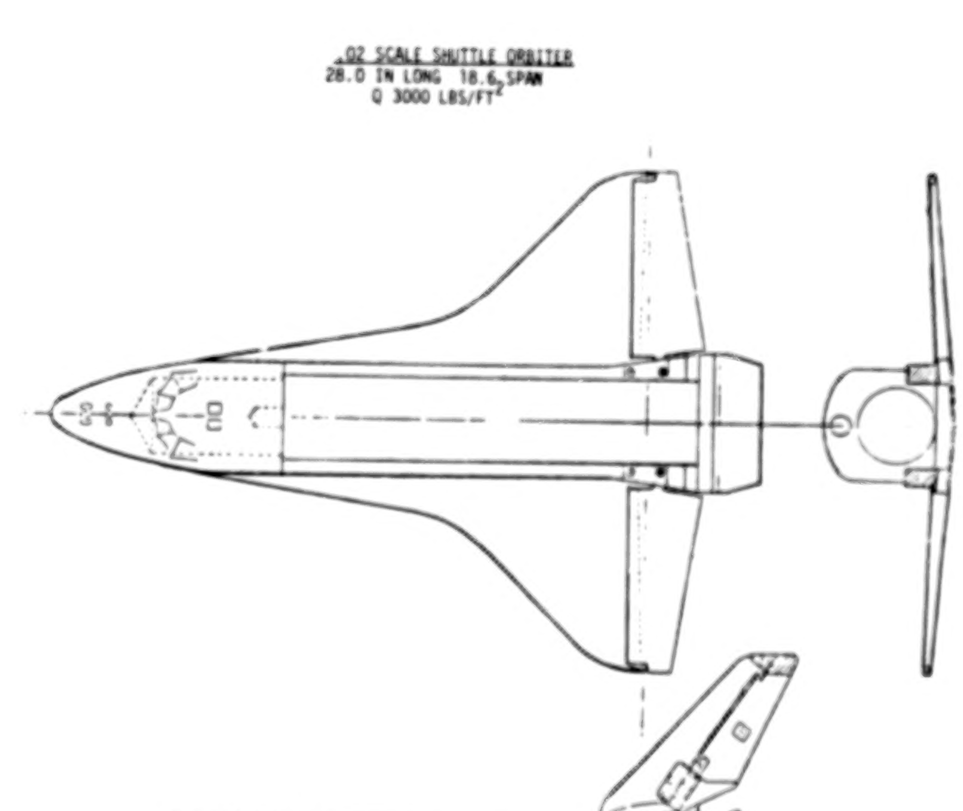


STRAKES (1 FLAT, 1 CAMBERED)



SHARP LEADING EDGE FLAP
(0° & 20°)

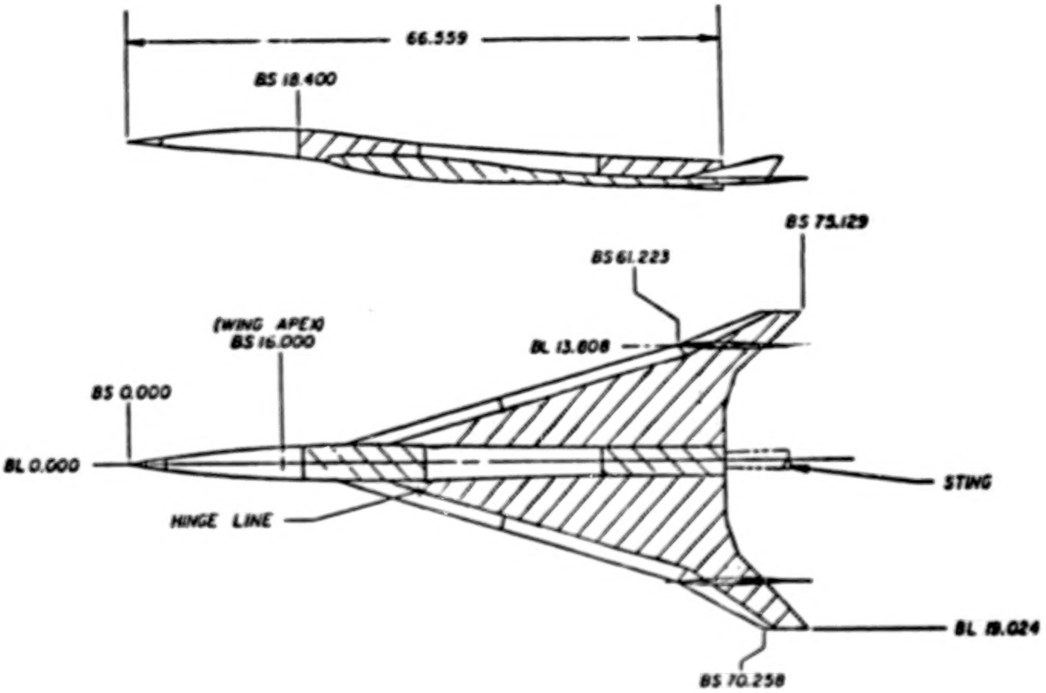
.02 SCALE SHUTTLE ORBITER
28.0 IN LONG 18.6 SPAN
Q 3000 LBS/FT^2



BEST DOCUMENT AVAILABLE

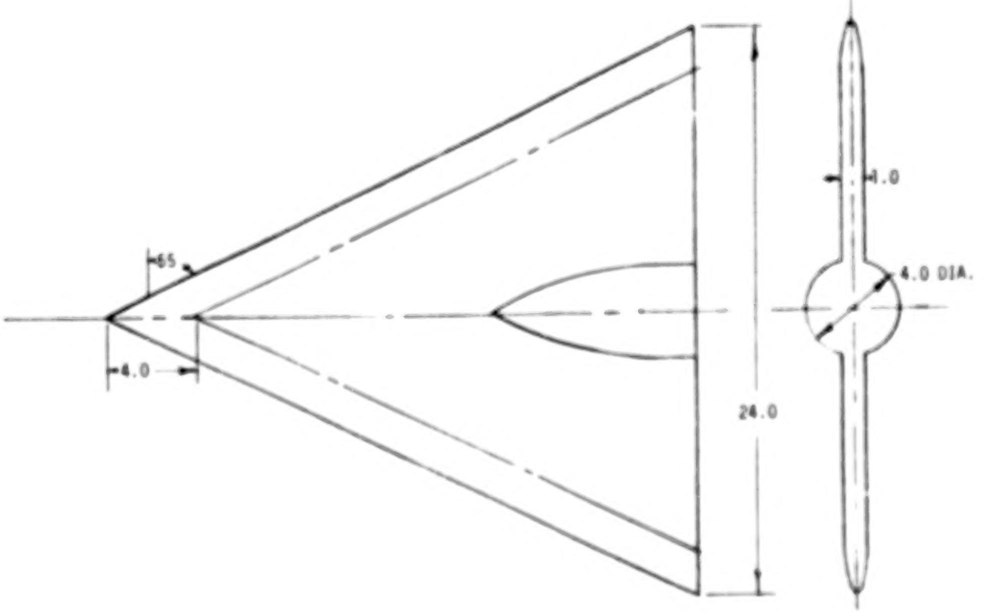
.025 SCALE SRC MODEL

M .3 TO 1.2   Q 2300 LBS/FT^2
MAX. NORMAL 3300 #


66.559
BS 18.400
BS 75.129
BS 61.223
(WING APEX)
BS 16.000
BL 13.608
BS 0.000
BL 0.000
STING
HINGE LINE
BL 19.024
BS 70.258

DELTA WING MODEL

M .2 TO 1.2   MAX. LOAD 6500 #


65
4.0
1.0
4.0 DIA.
24.0

STATUS OF MANEUVERABLE-FIGHTER MODEL DESIGN STUDY

Stan A. Griffin
General Dynamics, Convair Division
San Diego, California

A design study is in progress to develop high-technology fighter aircraft models for test in the National Transonic Facility (NTF) in order to make tunnel-to-full-scale data correlations. The selected configurations and scales are as follows: 1/15-scale F16XL for the single-engine configuration, and 1/20-scale F111 TACT for the twin-engine configuration. Both of the configurations at the selected scales have been tested extensively in transonic tunnels of a size comparable to the NTF, and these tests have provided a data base on which to make accurate force, moment, and loads predictions.

The NTF models will measure both force and pressure data. Pressure tap locations were selected after review of the flight test article and previous models. The study will be conducted in sufficient depth to insure that the models can be fabricated and will meet the design criteria for the NTF. In addition, model costs will be determined.

Critical areas of the models that affect cost and/or safety factors have been identified as follows:

1. Instrumentation bay - This will be an environmentally controlled bay housing the electronically scanned pressure (ESP) probes, the multiplexer, and the attitude sensor, and it will be maintained at room temperature. It will be constructed of Kevlar and will have local steel stiffeners at the joints.

2. Instrumentation bay to midbody joint - In this case the dissimilar materials used created a problem only in hoop tension, and additional screws were added. This joint must be insulated to maintaim room temperature conditions within the forward bay.

3. Wing - The wing is made of 18Ni-200 maraging steel, which is very difficult to work after aging. The complications of the thin wing and the need for installation and routing of pressure tubes necessitated a two-piece construction. A good surface finish is also mandatory, and the design effort has been directed toward attachment of the lower plate at a temperature less than the aging temperature (900°F). Various methods are being investigated, with emphasis on diffusion brazing. Final results are not available, but a fatigue test of a similar wing is planned.

4. Sting - A great deal of effort was expended on a composite sting design. However, problems with dissimilar materials indicated that for the moment this is not practical. A steel sting (18Ni-200) will be used which meets all requirements, but deflection is greater than is desired.

5. Surface finish - Present-day models have a finish of 16 to 32 μin., but the NTF will require a finish of 8 to 16 μin. This can be achieved, but it will be costly. Further degradation of the finish is caused by joint mismatch; an experiment revealed a potential mismatch of 0.002 in., which would be highly undesirable at the leading edge. Routing of pressure tubes in the wing surface will be limited, and the orifice size will be minimized (0.010 in. diameter).

To verify an acceptable design, "proof of concept" tests are planned. In one case a simulated wing will be fatigue tested at cryogenic temperatures to evaluate the diffusion-brazed joint. Concurrently, a series of tests will be run to evaluate filler materials, screw locking methods, tube installation methods, etc.

A second "proof of concept" test will investigate the heated instrumentation bay at cryogenic temperatures, and will ascertain whether room temperature conditions can be maintained. The assembly will also be subjected to a vibration test to simulate tunnel conditions.

This study to date indicates several conclusions.

1. Full-scale Reynolds numbers can be achieved with a model of an advanced fighter in the NTF.

2. Combined force and pressure models are feasible, depending on the aerodynamic configuration.

3. Relaxed criteria for safety factors are mandatory for achieving full-scale Reynolds numbers. However, this necessitates additional engineering to insure that the facility drive system is not endangered. On the other hand, too conservative a design approach will result in the tunnel not being used to its full potential.

4. Maintaining the instrumentation bay at room temperature can best be achieved by isolation and environmental control of the forward fuselage.

5. New manufacturing techniques should be developed under simulated NTF conditions prior to using them in a wind tunnel model. Such "proof of concept" tests can be very cost effective, and will be necessary to establish structural properties.

6. Maraging steel 18Ni-200 is the best high-strength steel suitable for NTF models. It can be obtained, but it is costly.

7. Complete profiling is necessary prior to aging. This is a goal worthy of special effort. Working 18Ni-200 in the aged condition is both difficult and costly.

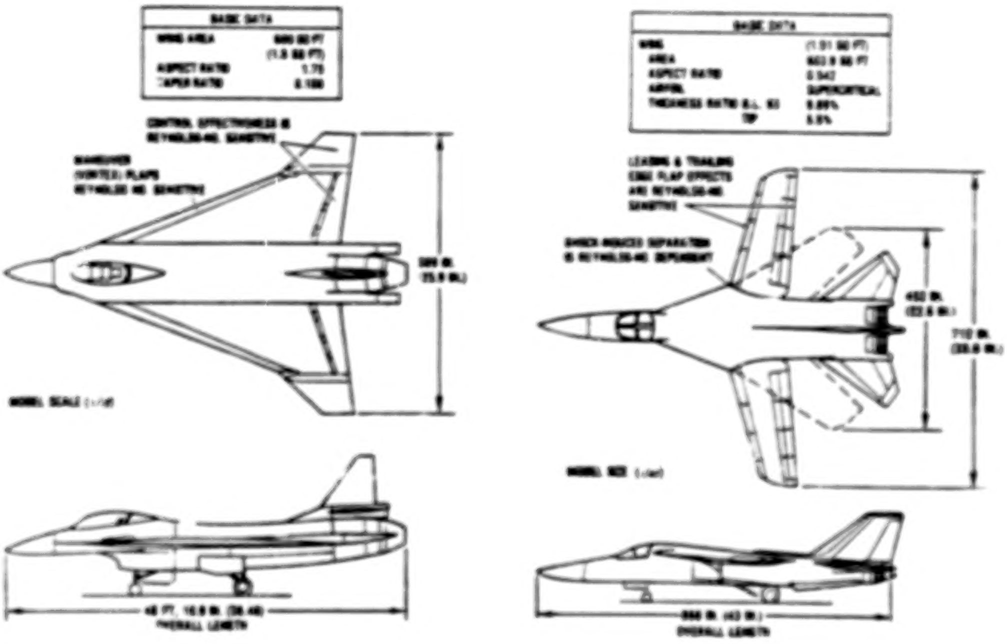
8. Use of dissimilar materials at low temperatures does not appear to be feasible. Thermal stresses and joint mismatches that are not acceptable will occur. Further effort is needed in this area because it directly affects model cost.

9. "Proof of concept" tests are planned to evaluate filler material, tube installation methods, and screw locking devices.

10. Models will be more expensive, particularly in the early years of tunnel operation. It is felt, however, that planned R&D efforts, experience gained in machining 18Ni-200, and increased use of computer-aided design and computer-aided machining techniques will all contribute to a subsequent reduction in model costs.

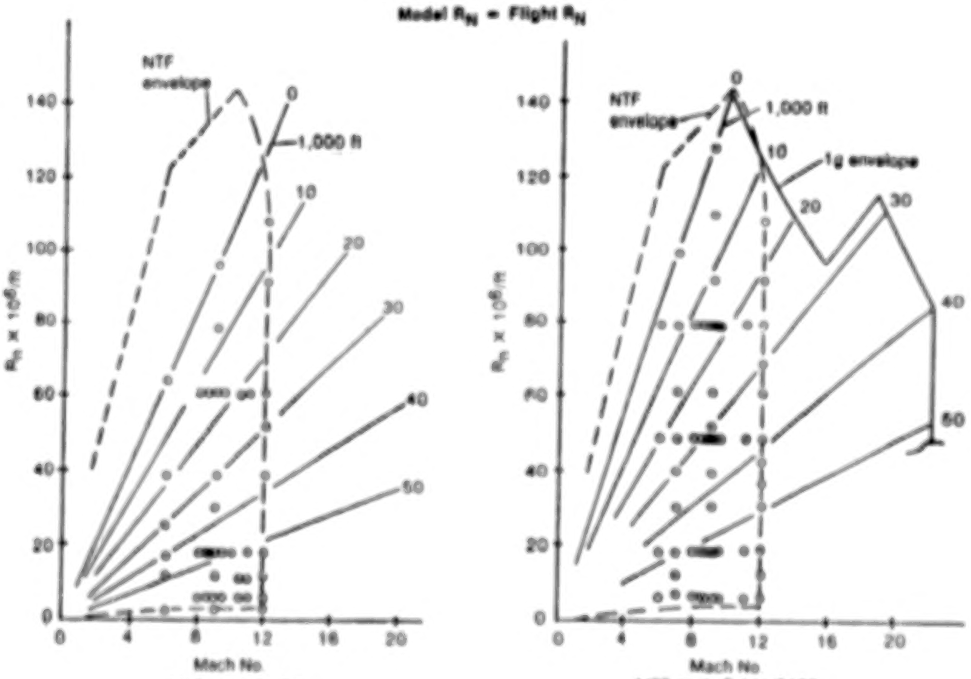
DESIGN STUDY OF TEST MODELS FOR NTF

Maneuvering aircraft configurations


BASIC DATA
WING AREA
ASPECT RATIO 1.75
TAPER RATIO
MODEL SCALE
OVERALL LENGTH
BASIC DATA
ASPECT RATIO
AIRFOIL SUPERCRITICAL
THICKNESS RATIO
TIP
OVERALL LENGTH

TEST POINTS F-16XL & F-111/TACT
NASA/LRC NTF

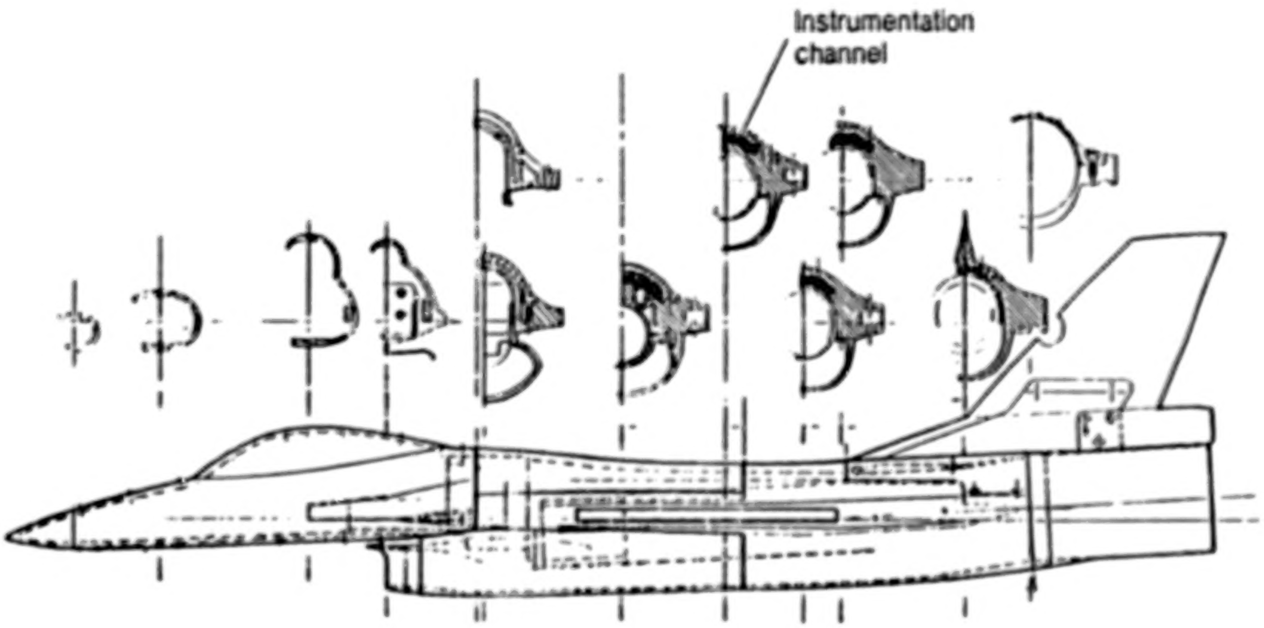
Model R_N = Flight R_N



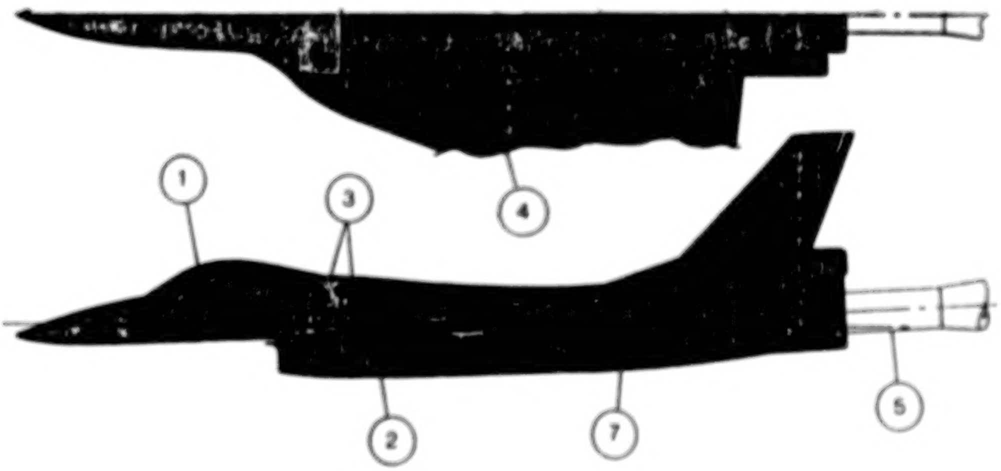
1/15 scale F-16XL

1/20 scale F-111/TACT

F-16E SIDE ELEVATION

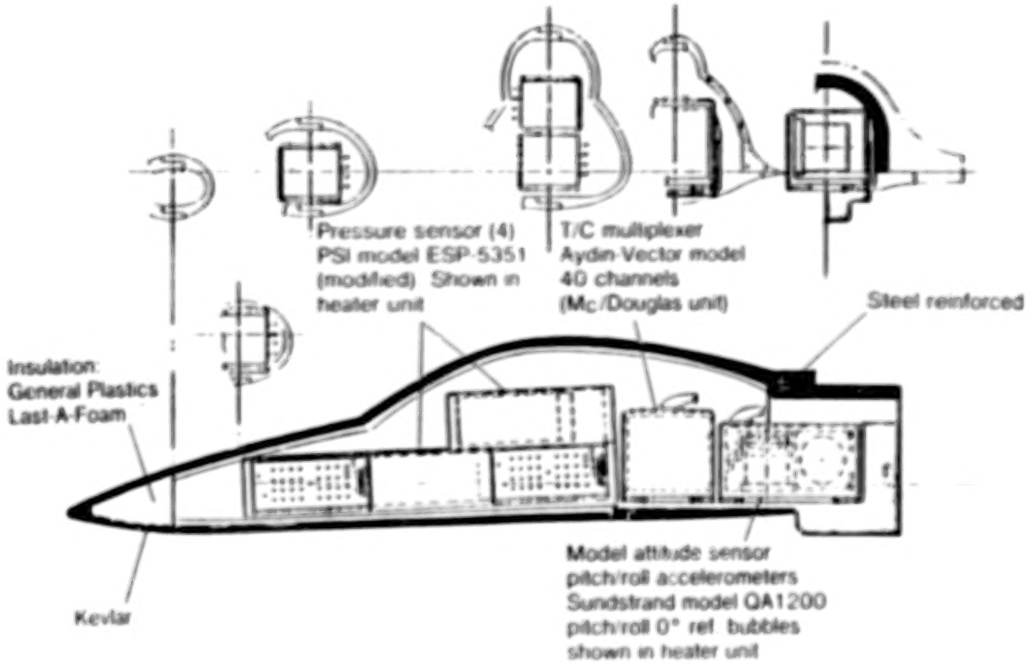


CRITICAL AREAS OF MODEL

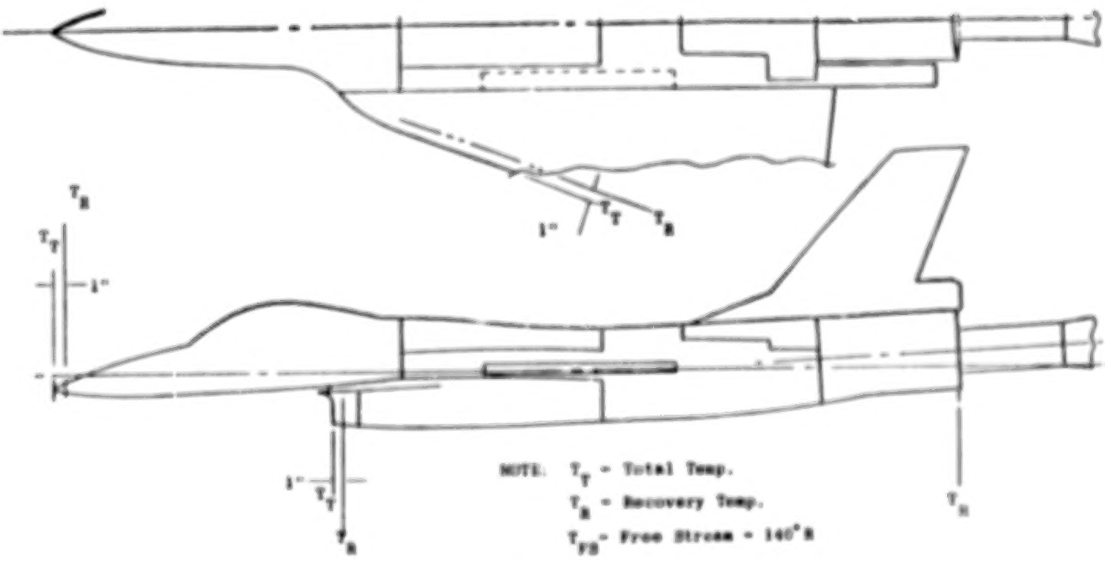


1 Nose/canopy instrumentation bay
2 Ducting — fabrication method
3 Nose/canopy to mid-body joint
4 Wing — fabrication method (pressure wing)
5 Sting — materials, fabrication method
6 Surface finish (8_{μ} inches to 25% to 16_{μ} inches)
7 Cable crossing balance
8 Joint mismatch/tube installation

ENVIRONMENTALLY CONTROLLED INSTRUMENTATION BAY
F-16E


Pressure sensor (4)
PSI model ESP-5351
(modified) Shown in
heater unit
T/C multiplexer
Aydin-Vector model
40 channels
(Mc/Douglas unit)
Steel reinforced
Insulation:
General Plastics
Last-A-Foam
Kevlar
Model attitude sensor
pitch/roll accelerometers
Sundstrand model QA1200
pitch/roll 0° ref. bubbles
shown in heater unit

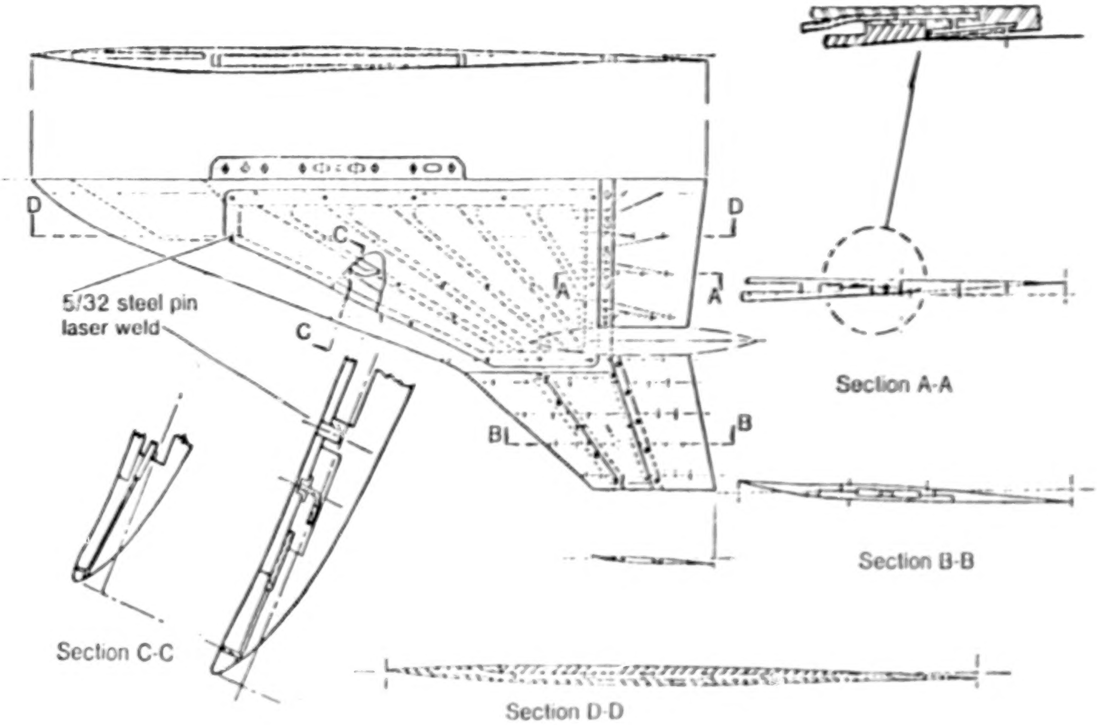
MODEL TEMPERATURE GRADIENTS


T_R
T_T
1"
T_T
T_R
1"
T_T
T_R
T_R

NOTE: T_T - Total Temp.
T_R - Recovery Temp.
T_{FS} - Free Stream - 140°R

M	α°	T_T	T_R	CIRCUMFERENTIAL TEMPERATURE GRADIENT		LONGITUDINAL TEMP. GRADIENT			
				UPPER	LOWER	FWD UPR.	AFT UPR.	FWD LWR.	AFT LWR.
1.2	0°	180°R	175°R	175°R	175°R	175°R	175°R	175°R	175°R
1.2	20°			175°R	140°R				
0.8	0°	157°R	154°R	154°R	154°R	154°R	154°R	154°R	154°R
0.8	20°	157°R	154°R	154°R	140°R				

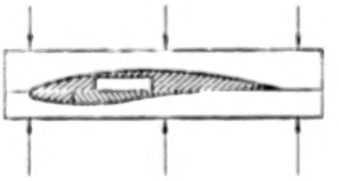
F16-E PRESSURE WING



WING FABRICATION METHODS
Wing 18Ni-200

Fabrication method	Adhesive foil	Fabrication process			Inspection method	Tooling	Estimated strength psi
		Temperature	Pressure	Time			
Adhesive bonding	American Cyanamid FM 1,000	300°F	50 psi	1 to 2 hours	Under development GD/FW	Minimum	4,000 to 5,000
Diffusion brazing		75°F 1,000°F	To be determined Approximately 1,000 psi	1 to 3 hours	Ultrasonic or C-scan	Ceramic profiled	10,000
Brazing	Gold alloy	1,800°F	Minimum		Ultrasonic or C-scan	Steel flat	50,000
Diffusion bonding	None	1,800°F	5,000 psi (example)	3 hours	Ultrasonic or C-scan	Steel profiled	70,000

Key parameters:
- Maintain surface finish
- Fabrication cost
- Complete wing profile before joining
- Tooling from wing profile
- Rework incomplete bond without scrappage/warpage
- Strength 6,000 to 10,000 psi
- Curing temperature less than 900 deg F
- Fatigue resistant



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ACHIEVED SAFETY FACTORS — TEST MODELS FOR NTF
1/15 F-16XL — 1/20 F-111 Tact
Minimum Acceptable S.F. 1.5 on Yield 2 on Ultimate

Part/Joint	Material	Achieved factors			
		Yield		Ultimate	
		Room temperature	140°R	Room temperature	140°R
F-16XL (screws) Fuselage Sta. 13.75 — joint(1)	A-286	2.0	2.3	3.1	4.2
Forward fuselage (Sta 12.75)(2)	Kevlar 49	—	—	5.1/2.2	—
Wing section — spanwise	Diffusion brazing	—	—	—*	2.7*
Wing section — SS 9.14	Diffusion brazing	—	—	—*	2.2*
Wing control surfaces (screws)	A-286	2.4	2.9	3.9	5.3
Sting support	18NI-200	5.0	6.6	5.1	6.8
F-111 Tact Wing section - SS 6.200	Diffusion brazing	—	—	—*	1.7*
Wing pivot (screws)	A-286	2.0	2.4	3.2	4.3
Horizontal tail — remote control(3)	18NI-200	1.6	1.8	1.7	1.8

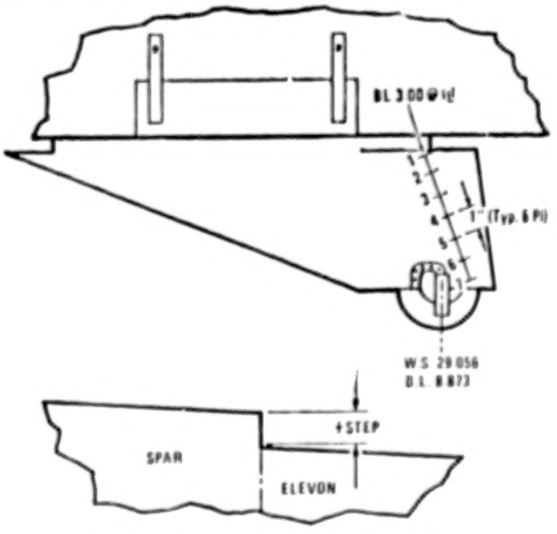
*Proof of concept tests

(1) Add screws

(2) Make thicker section or line with steel strips

(3) Brackets — fixed locations

JOINT MISMATCH PRODUCED BY WING DEFLECTION



- MAX LOAD CONDITION
- M = .90 α = 22° q = 1418 psf
- WING PANEL LOAD = 1381#

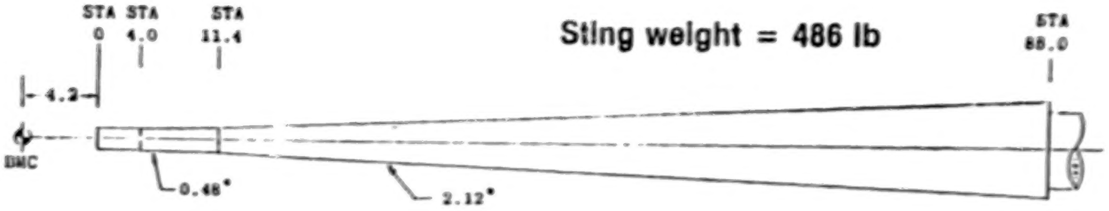
- 520# CONCENTRATED LOAD PRODUCES TIP DEFLECTION EQUIVALENT TO 1381# DISTRIBUTED LOADS

STA	STEP @ 0#	STEP @ 520#	ΔSTEP
1	.00700	.00700	.00000
2	.00000	.00100	−.00100
3	.00175	.00300	−.00125
4	.00400	.00225	+.00175
5	.00375	.00325	+.00050
6	.00425	.00400	+.00025
7	.00250	.00025	+.00225

(Note: All Dimensions in Inches)

BEST DOCUMENT AVAILABLE

STING DETAIL

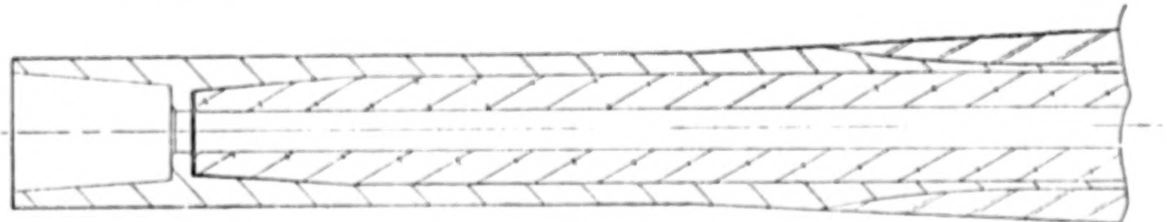


STA, in.	O.D., in.	F_b, psi	A286				18Ni 200			
			RT		140°R		RT		140°R	
			AF	°Defl	AF	°Defl	AF	°Defl	AF	°Defl
0.0	2.0	37,898*	2.6	3.23	3.2	3.23	5.4	3.35	7.1	3.19
4 0	2.0	51.543	1.9	2.90	2.3	2.90	4.0	3.01	5.2	2.86
9.1	2.086	65,710	1.5	2.32	1.8	2.32	3.1	2.45	4.1	2.29
11.4	2.125	70,084	1.4	2.03	1.7	2.03	2.9	2.10	3.8	2.00
29.5	3.466	32,060	3.1	0.73	3.7	0.73	6.4	0.76	8.4	0.72
55.0	5.355	14,600	6.8	0.31	8.2	0.31	14.0	0.23	18.5	0.21
85.6	7.622	7,650	13.1	0.01	15.7	0.01	36.8	0.01	35.5	0.01

*Tensile stress from socket analysis

COMPOSITE STING

- Based upon material thickness of 0.080,maximum.



	Fty (ksi)		E (msi)		(in/in/F)(10^{6})	
Material	R.T.	140 R	R.T.	140 R	R.T.	140 R
▨ 18Ni 200	208	270	26.2		5.6	
▨ Kennametal K-9	100		94		2.0	
▨ Boron / Aluminum	208*		32.2*		1.2 L 5.0 T	
▨ Alternate	160		45			

BEST DOCUMENT AVAILABLE

PRESSURE TAP INSTALLATIONS AND FILLER MATERIALS EVALUATION
ON TEST SPECIMEN (SIMULATED WING PANEL)

TAP INSTALLATIONS

1. BRAZE PLUG - LOW TEMPERATURE
2. WELD PLUG - LASER WELD
3. TUBE BRAZE - LOW TEMPERATURE
4. EDM HOLE

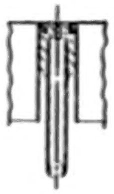
FILLER MATERIALS

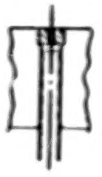
SCREW HEADS

5. EA 934
6. DEVCON F - STEEL FILLED
7. KWIK KURE
8. WHITE LIGHTNING

SLOTS

9. DEVCON F - STEEL FILLED
10. SOLDERS - VARIOUS


1.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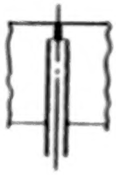
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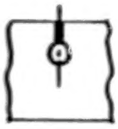
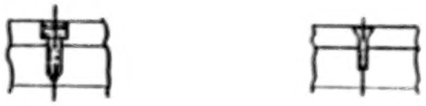
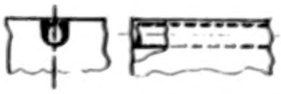

4.


5.,6.,7.,8.


9.,10.

COST COMPARISONS
Conventional Pressure Model/NTF Model

	Manufacturing	Engineering	Weighted cost ratios	Cost factor NTF
Analysis Aero/Thermo/Loads Stiffness		X	.75	1
Design-stress analysis Configuration definition		X	2.75	5
Manufacturing Raw material Machining (milling) Surface finish Tolerances Pressure tube routing Thermal cycling Fasteners/filler materials	X		5.50	12
Structural testing Environmental testing	X	X	.0	1
Instrumentation Pressure measurements Buffet-thermocouples On-line loads monitoring	X	X	.5	1
Quality control Raw material-documentation Model inspection		X	.5	1
		Total	10	21

CONCLUSIONS

1/15 F16XL and 1/20 F111 TACT can achieve full-scale RN

Pressure models are feasible - number of taps limited by configuration

Combined force/pressure models feasible but configuration sensitive

Relaxed safety factors and increased analysis needed for full-scale RN

Environmentally controlled instrumentation bay needed

Thermal gradient across model increases with α

Many present-day techniques are acceptable - use them

Use proof-of-concept tests to develop new methods, processes

Vendor information cannot always be accepted at face value

Selected steel 18Ni-200 - high strength (R.T./140^{o}R) - stability - toughness

Cost effective - complete profiling prior to aging

Dissimilar materials desirable but not practical

Further research needed - filler materials - tube installation - diffusion brazing

Model costs will be 2.1 greater; this will be reduced by further R&D and experience with early models

LANN WING DESIGN

George C. Firth
Lockheed-Georgia Company
Marietta, Georgia

The LANN wing is the result of a joint effort between Lockheed, the Air Force, NASA, and the Netherlands to measure unsteady pressures at transonic speeds. It is a moderate-aspect-ratio (8) transport wing configuration. The wing was machined from NITRONIC 40 and has 12-percent-thick supercritical airfoil sections. The wing has a semispan 1 m in length, a root chord of 0.361 m, a tip chord of 0.144 m, and a planform area of 0.25 m^2. The wing has a 1/4-chord sweep angle of 25^0 and a linear twist from root to tip of 4.8^0.

Static and oscillatory pressures were measured on the LANN wing in the high-speed tunnel at NLR (the national aerospace research organization) in the Netherlands in December 1981 using the NLR-developed "Matched Tubing Technique." Measurements were made for M_∞ from 0.62 to 0.95 at angles of attack from -0.4^0 to $+6^0$. The design condition for the wing is for a C_L of 0.53 at a Mach number of 0.82. The data from these tests will be used in defining the test boundary in the NTF. The instrumentation used at NLR is not appropriate for the NTF tests and will be completely replaced after the wing has been received at Langley.

The data from this wing will be the first unsteady wind tunnel measurements made at realistic Reynolds numbers, and the primary objective of the tests will be to determine, which as much precision as possible, what the effects of Reynolds number are on the unsteady pressure of a wing ocsillating in pitch.

LANN WING

Oscillating Unsteady Pressure Wing

CONFIGURATION VARIABLES

- o Aileron deflection
- o Engine nacelle
- o Wing-tip fins

TEST VARIABLES

- o $M = .6, .7, .76, .82, .85, .95$
- o $C_L = .3, .5, .7$
- o $Re = 6 \times 10^6 -- 60 \times 10^6$
- o Reduced frequency 0 to .2
- o B. L. transition fixing

MEASUREMENTS

- o 5 Component strain gage balance
- o Unsteady wing pressures (200)
- o Wing temperatures (15)
- o Wing accelerometers (9)
- o Wing root buffet gage
- o Static deformation

CONFIGURATION

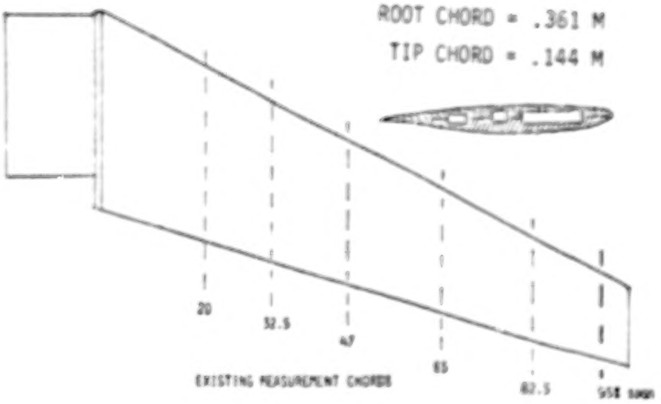
$t/c = 0.12$

$\Lambda_{\frac{c}{4}} = 25^0$

SEMISPAN = 1 m

ROOT CHORD = .361 M

TIP CHORD = .144 M



TEST OBJECTIVES

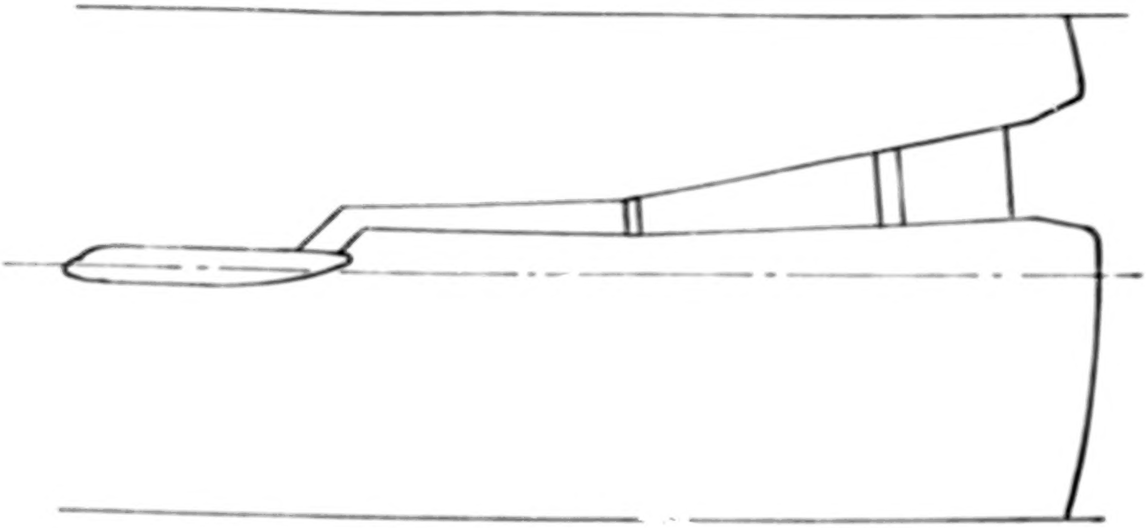
- o Reynolds No. effects on in-phase and out-of-phase aerodynamic forces and moments
- o Shock travel, flow separation, and buffet
- o NTF-NLR HST-Lockheed CFF data comparison

NTF MODEL: A NEW BREED

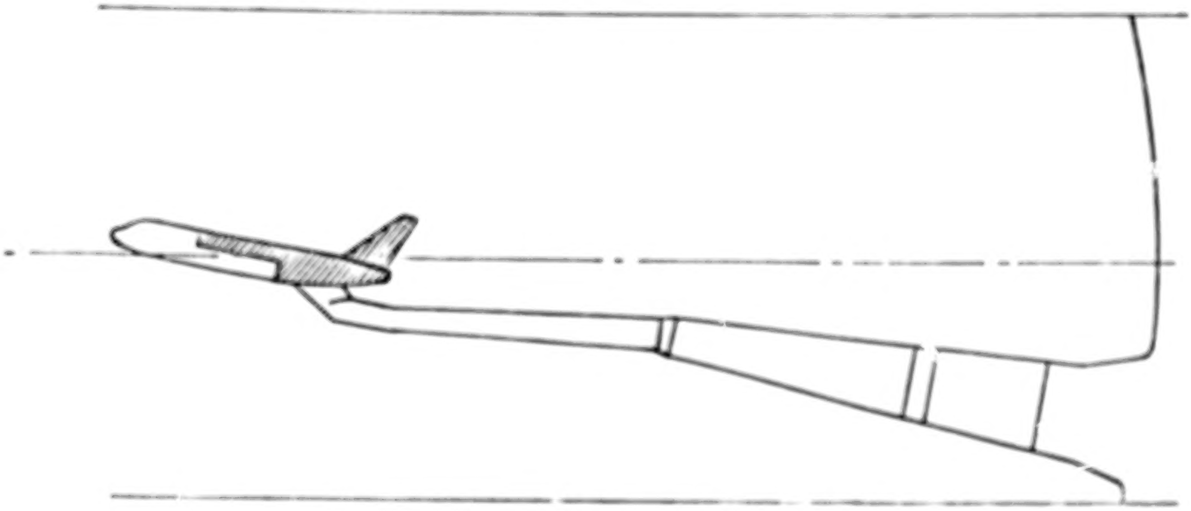
William C. Whisler
The Boeing Company
Seattle, Washington

This presentation will discuss Boeing's experience with high-R_N and cryogenic models, as well as the current Boeing 767 model for the National Transonic Facility. Design considerations due to low temperatures are mentioned, and the importance of careful, well-thought-out design is emphasized. Some details regarding thermal aspects, close fits, tight tolerances, and the extent of analysis required are also pointed out. Some specifics of fabrication, including use of VM200 steel, tolerances, and surface finish, are mentioned.

UPPER SWEPT STRUT INST'L (N T F)



LOWER SWEPT STRUT INST'L (N T F)



Boeing 767 model for NTF

NTF MODEL CONCEPT FOR THE X-29A

Gianky DaForno and Gene Toscano
Grumman Aerospace Corporation
Bethpage, New York

This workshop on cryogenic models will, in essence, bring the Grumman X-29A NTF model design concept phase to a close. The next phase will be a full-detail design effort that will provide drawings ready for model fabrication.

The entire study to develop a 6.25-percent scale model began in September 1981 when NASA Langley expressed interest in new flight test programs for NTF flight correlation aircraft. On this basis, and with concurring interest from Grumman's Advanced Development Section and Engineering Technology Committee, we proceeded with an initial concept drawing, which was further developed with the most up-to-date technical information available from the NASA Langley Model Design Group of the Systems Engineering Division.

We then embarked on a proof of concept by physical demonstration of those areas in the design that were most innovative relative to conventional wind tunnel model design. In particular, these are (1) the installation of pressure tap passages in the wing via an electron discharge machining (EDM) process to drill the holes, and (2) the electron beam (EB) welding of the wing tips to close the access area for EDM drilling. The demonstration module of these processes is presented in the illustrations.

Because of the concern to obtain the prescribed level of Charpy impact value (25 ft-lb at cryogenic temperature) in Vascomax 200 material, we produced a few Charpy samples containing a transverse EB weld at the V-notch location. Three tensile specimens containing a transverse weld were also produced. These samples were tested by NASA Langley at cryogenic temperatures prior to the workshop. The welded Charpy samples resulted in average impact values of 20 ft-lb for our heat treat cycle. This average value is as good as the NASA test samples with the base metal. The tensile specimens broke at slightly higher loads than had been calculated. It was noted in the presentation that the Charpy specimens did not come up to the prescribed level of 25 ft-lb. The results of the specimen tests are presented in the illustrations.

PART I

REQUIREMENTS, GUIDELINES, AND DESIGN LOADS

G. DaForno

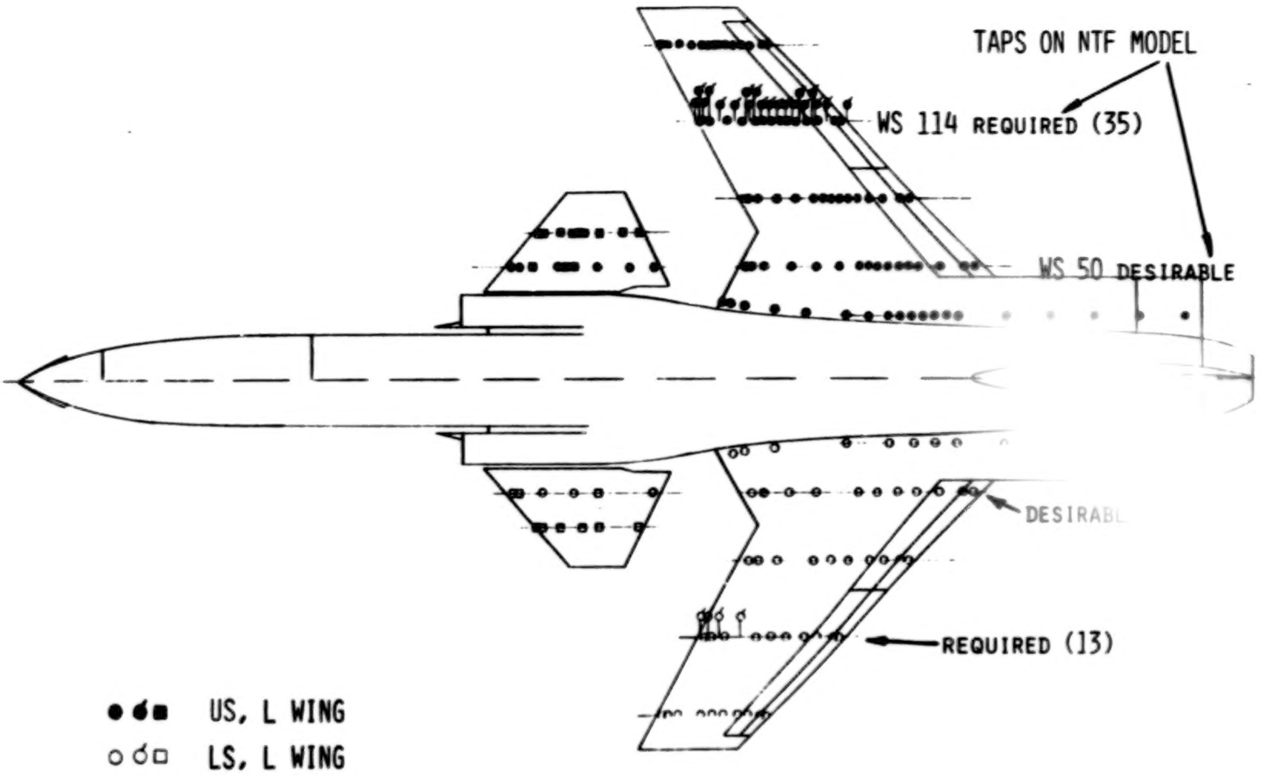
The main use of the model will be to acquire high-quality data for the NTF-to-flight correlation and, compatible with the schedule, to obtain highly desirable data for the X-29A project. The task of designing and fabricating a high-quality X-29A model for this use is challenging enough that we must resist the temptation to add more demands. Even though a key capability of the NTF is (static) aeroelastic studies at fixed Reynolds number, this model is not thought of as a tool for such studies. The philosophy of the effort is summarized in the figure.

PHILOSOPHY

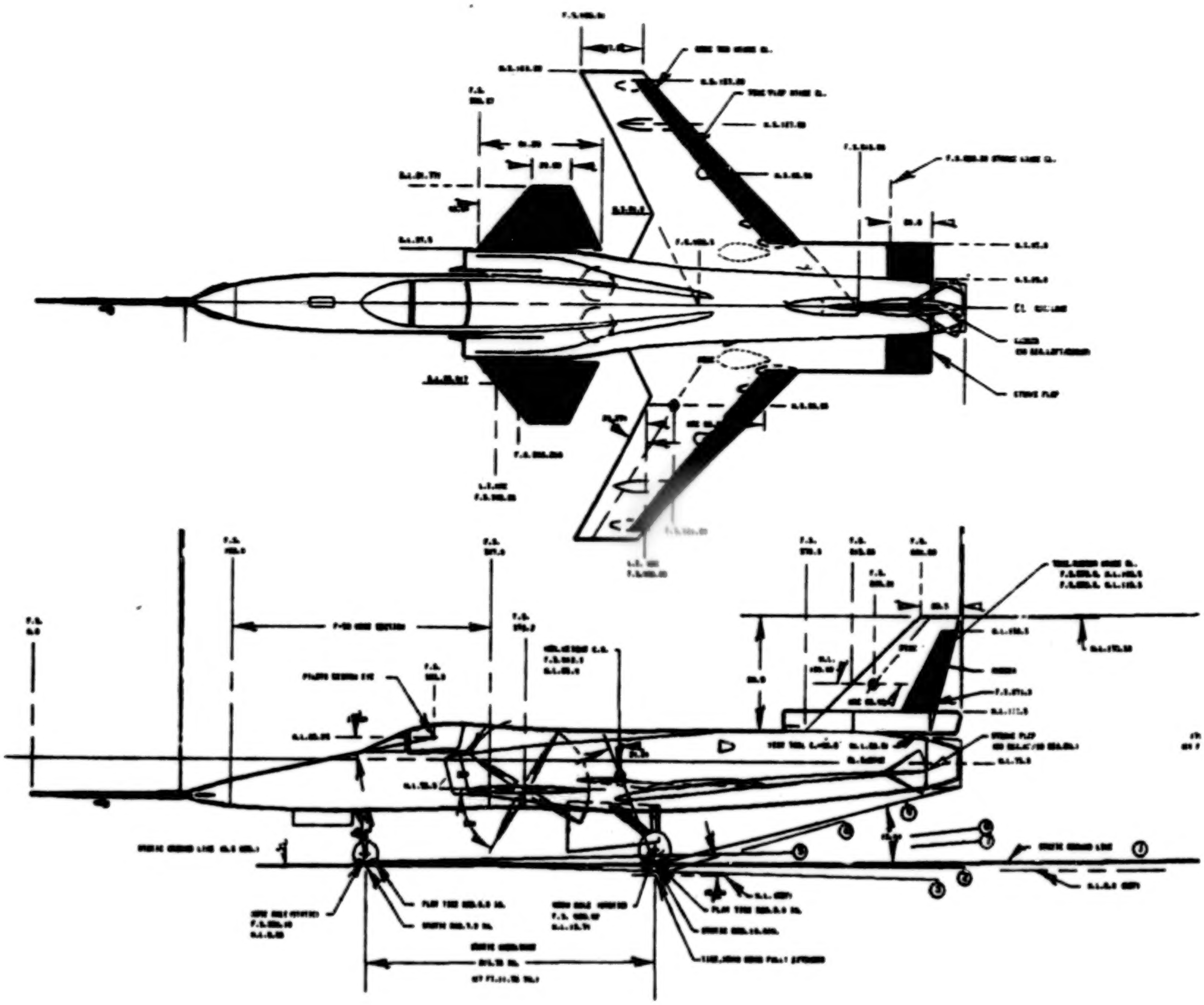
- DATA FOR NTF CORRELATIONS
  - NTF TO FLIGHT: PRESSURES AT ONE SPAN STATION (AT LEAST)
  - NTF TO OTHER TUNNELS
  - NTF, CRYO TO AIR
- FLIGHT-RE F&M DATA FOR X-29A PROGRAM
  - LOW-SPEED, HIGH α PITCHING MOMENTS
  - SUSTAINED AND INSTANTANEOUS MANEUVERING
  - CRITICAL MANEUVER LOADS
  - DRAG WITHOUT FLAP HINGE FAIRINGS
- MINIMUM DEMANDS ON MODEL, BUT HIGH QUALITY
- NO Q STUDY PER SE

Pressures are key to the correlation. This figure compares pressure tap locations on the model and on the flight article. On the flight article, the taps are only on the left wing/canard, and those marked with a tagged symbol were specially inserted for the NFT-to-flight correlation. The taps on the model are split left and right, as shown. It seems feasible to place on the model the taps marked "desirable."

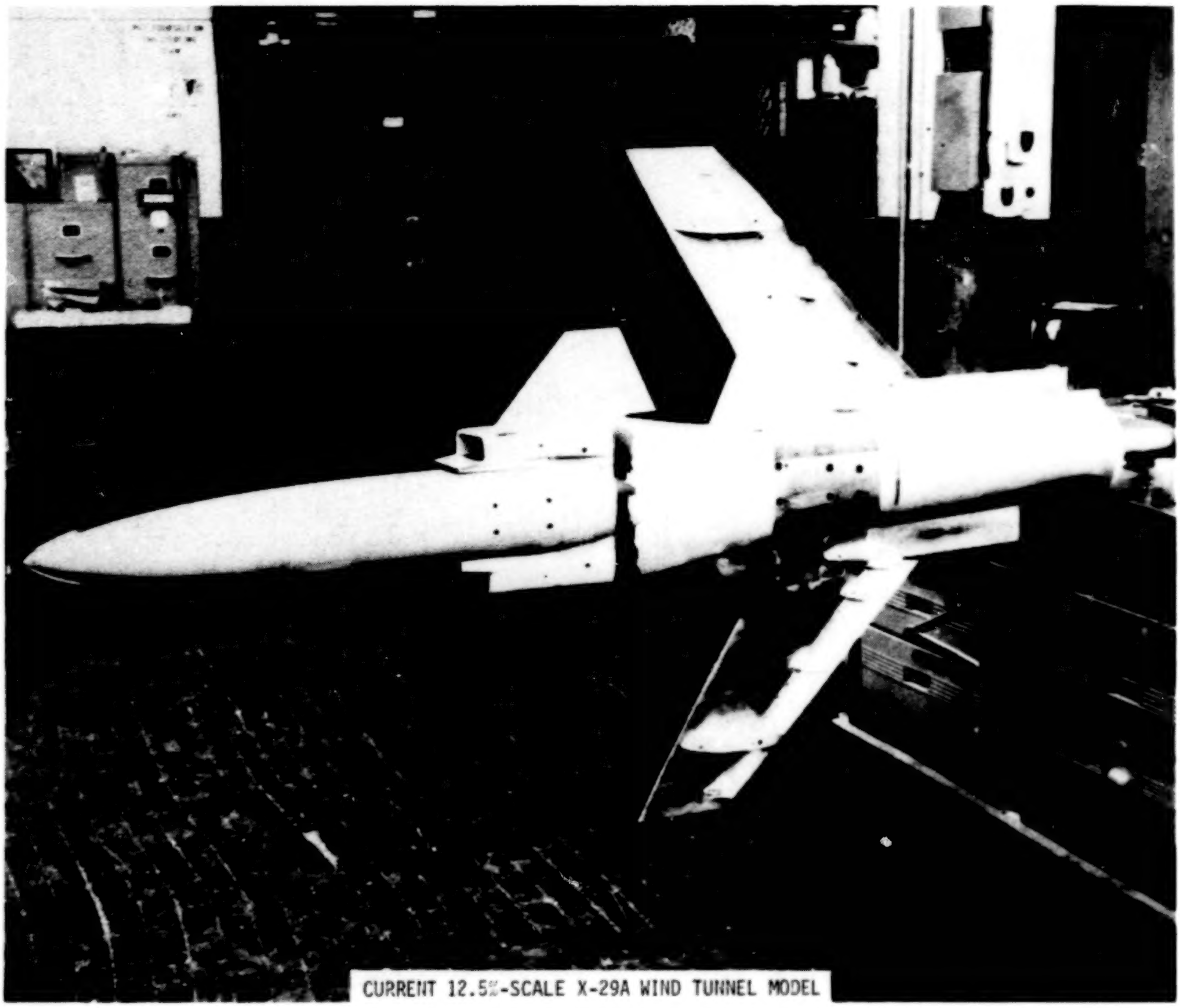
PRESSURE TAPS ON X29A AIRCRAFT


TAPS ON NTF MODEL
WS 114 REQUIRED (35)
WS 50 DESIRABLE
DESIRABLE
REQUIRED (13)
● ■ US, L WING
○ □ LS, L WING

An NTF-to-flight corelation requires the incorporation on the model of all controls which are here shown shaded.



Among the typical details to be included in the model for a realistic correlation effort are flap-tab actuator/linkage fairings (if any), since they have a distinct effect at least on drag. Size and number of such prospective fairings can be appreciated from this photograph of the X-29A (1/8 scale) Documentation Model.



CURRENT 12.5%-SCALE X-29A WIND TUNNEL MODEL

The motivation and philosophy for this model are translated into the set of requirements spelled out in this figure. Note the q range allowed. Data with removed fairings are of unique interest since the X-29A actuation is an off-the-shelf rather than an advanced item, and it would be desirable to establish the associated drag penalty at flight Reynolds numbers.

REQUIREMENTS

- COVER FLIGHT-RE FOR WORSE CASE:
  - LOW SPEED, HIGH α (M = 0.4, α TO 90°, β TO 25°, Re_{MAC} TO $20.6\text{x}10^{6}$)
  - MAX SUSTAINED G, INCL. MDP (M = 0.7 TO 1.00, α TO 7°, β TO 10°, Re_{MAC} TO $50\text{x}10^{6}$)
  - MAX INSTANTANEOUS G (M = 0.4 TO 1.1, α TO 45°, β TO 10°, Re_{MAC} TO $55\text{x}10^{6}$)
  - MANEUVER LOADS DESIGN CONDITIONS FOR WING, CANARD, VTAIL
- NTF-TO-TUNNELS CORRELATION: ALLOW FOR MAX UNIT RE OF 11 FOOT/16T/12 FOOT/NTF-AIR
- Q EFFECTS AND RE SENSITIVITIES: RANGES ARE FALL-OUT
- WING PRESSURE TAPS: 48 W.S. 114 + (DESIRABLE) 27 AT W.S. 50
- INCORPORATE ALL CONTROLS AND DEVICES
  - CANARD, 3 δ_c
  - WING TE FLAPS, 4 SETS
  - RUDDER, 4 δ_R
  - STRAKE FLAP (DESIRABLE)
- REMOVABLE FLAP HINGE FAIRINGS (DESIRABLE)

The motivation and philosophy for the model are further translated into guidelines to be kept in mind in satisfying the requirements. On contour fidelity, tolerance demonstrated (to a certain extent) at Grumman on a high-quality model includes: 1 mil on wing leading edges (via hand refinement of aluminum leading edges of somewhat larger radius), and 2 mils on wing large areas. Body-alone data are very desirable on the X-29A configuration, and giving this up is a price worth paying only for substantial other advantages.

GUIDELINES

- MIN Q (ONSET OF SATURATION), MIN T_T AND MINIMUM THERMAL STRESSES
- SCALE: MAX SIZE, COMPLETELY SAFE FOR WALL INTERFERENCE
  (EVEN AT THE COST OF REMOTE ACTUATION OF CANARD)
- MIN CONFIG BUILD-UP: CANARD OFF, V-TAIL OFF
- BEST MODEL TOLERANCES DEMONSTRATED, BUT NO EXTRA DEVELOPMENT
- (PROVISIONAL):
  - 3 T/C
  - NOSE STRAKES AND BOOM
  - NO BUFFET GAGES
  - NO RMS ROLLING MOMENT
  - STRAIN GAGES FOR MONITORING INTEGRITY
  - ROOT GAGES?

The point of this figure is to draw attention to the fundamental elements which determine the mechanical and thermal loads on the model. They are: the decision on the scale, the flight conditions to be simulated, and the trade-offs (q versus temperature) in the test section. Of course, we strive for minimum loads. There is a minimum value of $c_N q$ once flight c_N's and associated Reynolds numbers are given. Also, as soon as Re_{MAC} is in the range 20×10^6 and up, thermal loads close to the NTF lowest temperatures are unavoidable and therefore we accept the maximum thermal loads in exchange for minimum $c_N q$.

$$\text{DESIGN LOAD} = \left\{ \frac{S_{REF}}{F.S.} \cdot \text{SCALE} \right\} \cdot \left(c_N q \right)_{DES}$$

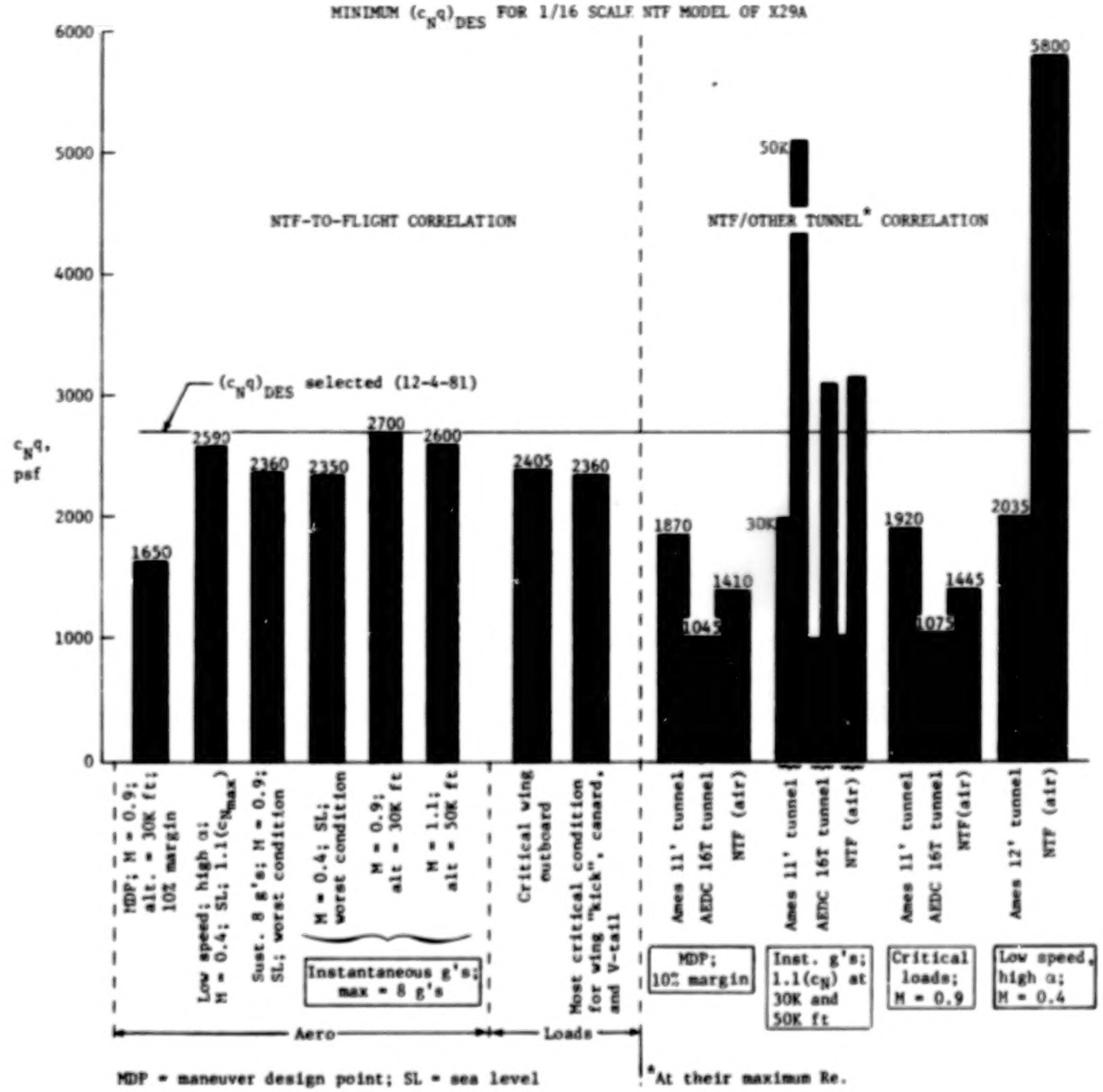
THERMAL LOAD T_t

In order to have maximum volume for instrumentation, highest strength, easiest fabrication, and best line fidelity for given fabrication tolerances, this scale was chosen as the largest that seemed safe for wall interference. The 1/16 scale choice relies on NASA Langley guidance emphasizing prudence at the present time against transonic wall interference. Little information exists on scale requirements for high-angle-of-attack low-speed wall interference in slotted-wall tunnels. Typical (geometrical) blockage values of Grumman practice with conventional models are given merely as reference. Remote control of the canard is impossible in a 1/16 scale model, but it may have been possible in a 1/12 scale model.

SCALE (WALL INTERFERENCE)

- TRANSONIC SPEEDS, LOW α
  - → 1/16 SAFE — $\bar{c} = 0.05\sqrt{A_{TS}}$; $b/W = 0.20$
  - 1/12 MAX REASONABLE SIZE, BUT CONCERN — $\bar{c} = 0.07\sqrt{A_{TS}}$; $b/W = 0.27$
- LOW SPEED, HIGH α SEEMS OK
- CONVENTIONAL GRUMMAN MODELS:
  - TRANSONIC, FOR 8' TUNNELS — $\bar{c} = 0.075\sqrt{A_{TS}}$ to $0.095\sqrt{A_{TS}}$
  - LOW SPEED, HIGH α FOR 7' x 10', SOLID WALLS — $\bar{c} = 0.06\sqrt{A_{TS}}$ to $0.11\sqrt{A_{TS}}$; $b/W = 0.11$ to 0.33

We take the onset of saturation (as shown in the NTF projected operating envelope) as a reference minimum q at each Reynolds and Mach number. To keep $(c_N q)_{DES}$ at a minimum, it is necessary to choose at the outset the flight conditions to be simulated. This figure shows that a $(c_N q)_{DES}$ emerges quite naturally, since a value around 2700 psf is required by the majority of the conditions. The normal load is only 1950 lb.

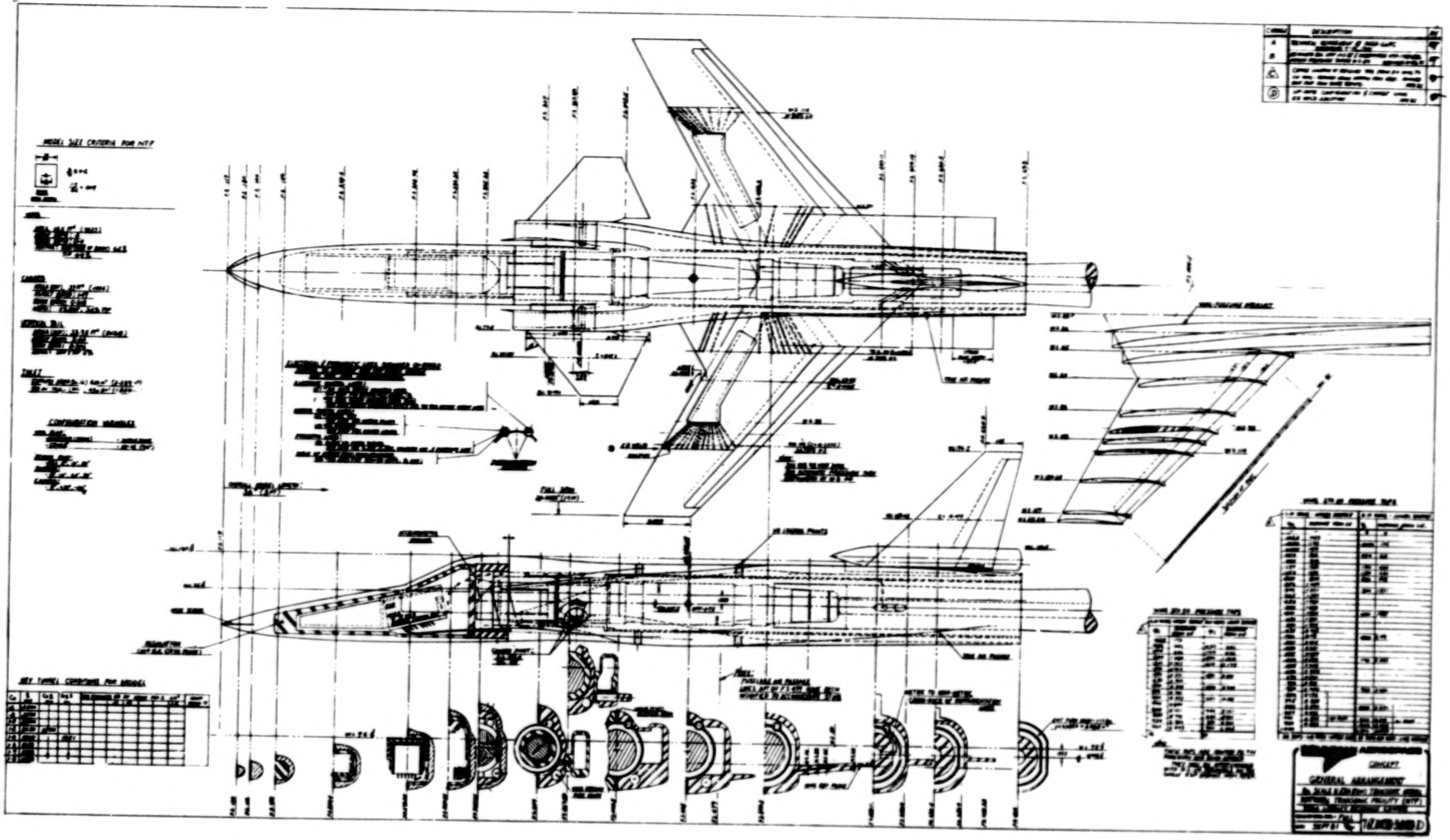


PART II

DESIGN AND FABRICATION CONCEPT

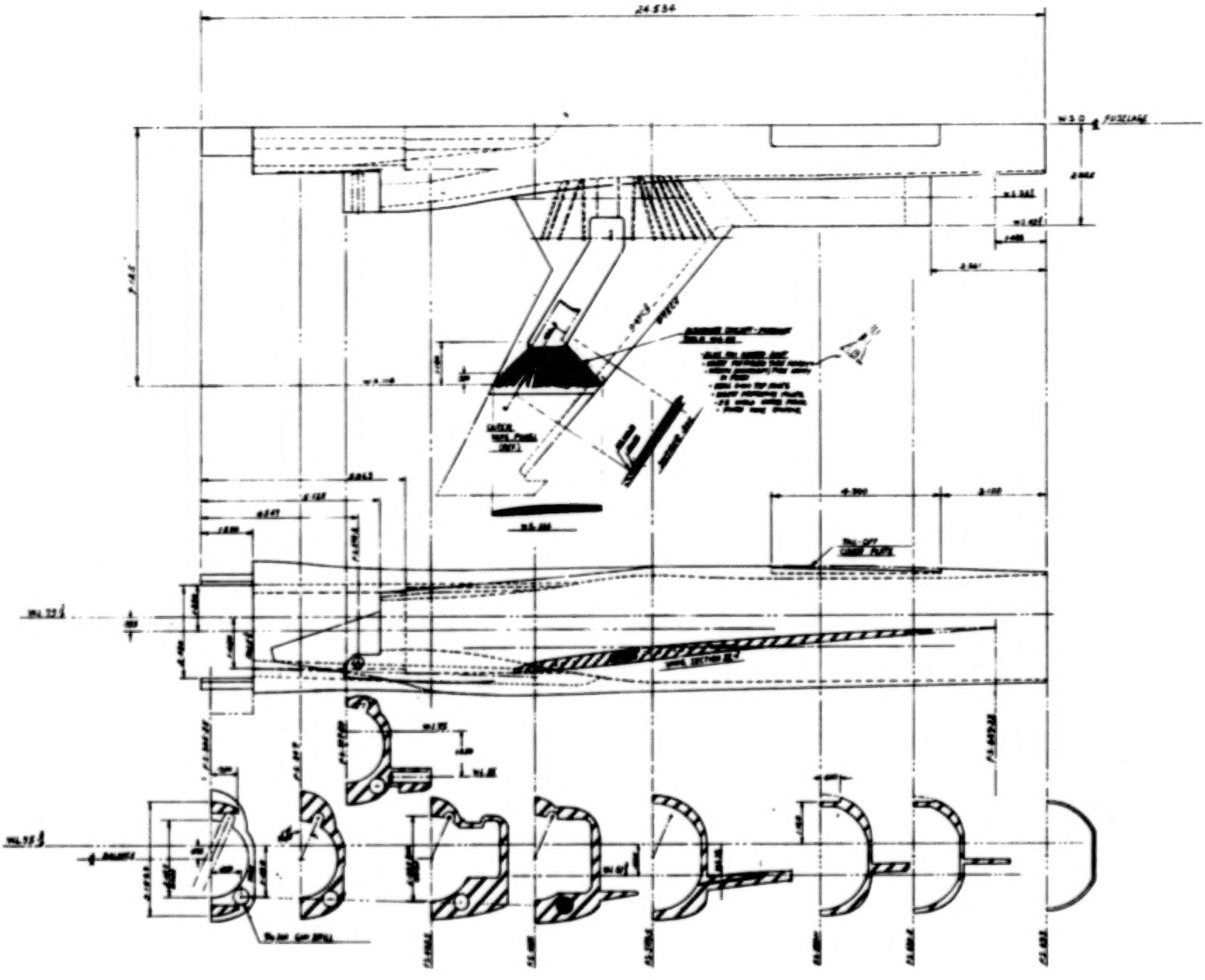
E. Toscano

The first concept of this drawing was done in September 1981 to determine if a small model to fit the NASA Langley sizing criteria could accommodate the aerodynamic and mechanical requirements prescribed in Part I of this presentation. For a model wing span of 1.7 ft (and a length of 3 ft), the model is 6.25 percent (1/16 scale). The results were encouraging enough for Grumman to request, in early December 1981, that the design concept be refined at NASA Langley, where up-to-date cryogenic model design information was available. This working session was completed by a Grumman designer by mid-December. In its present form, the concept will be the basis for any continued effort.


MODEL SIZE CRITERIA FOR NTF
CONFIGURATION VARIABLES
FULL SCALE
CONCEPT
GENERAL ARRANGEMENT
NATIONAL TRANSONIC FACILITY (NTF)

BEST DOCUMENT AVAILABLE

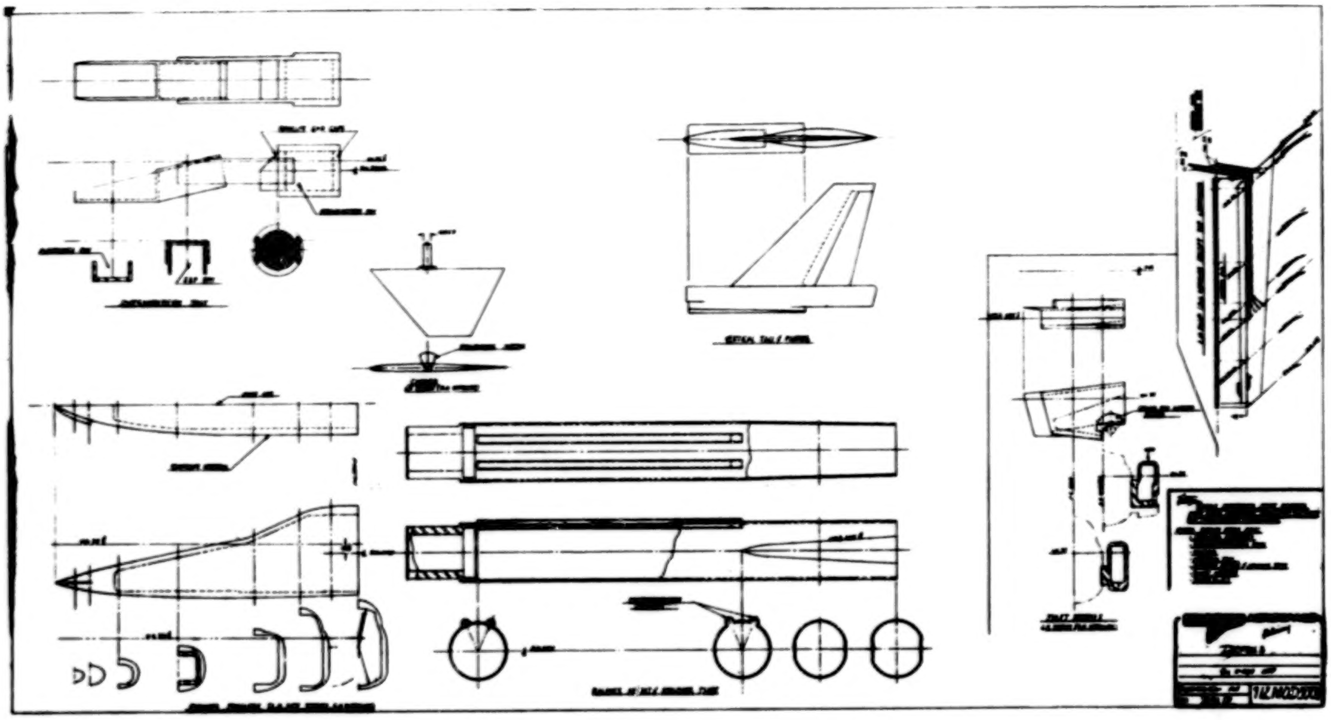
This drawing is a preliminary detail of the major model structure which embodies the monocoque concept. The purpose of the drawing is to give the visibility needed to develop a first-cut design and fabrication cost.



NOTE:
THIS DRAWING IS FOR ESTIMATING PURPOSES ONLY. [illegible]

[illegible]

For the same purpose of developing first-cut model costs, this drawing shows all the other detail parts in preliminary form.



As a result of the three previous drawings, the model hardware and pressure instrumentation features were developed into this chart for ready reference in continued discussion and in any further detail design.

MODEL CONCEPT FEATURES

- MONOCOQUE STRUCTURE
  - INTEGRAL WING-BODY, 64% LENGTH } MINIMIZES MECHANICAL JOINTS
  - ONE PIECE INSULATED FWD FUSELAGE, 36% LENGTH } MINIMIZES MECHANICAL JOINTS
  - EB WELD OF FUSELAGE
  - EXTERNAL MECHANICAL JOINTS: FWD FUSELAGE, FLAPS, VERTICAL TAIL, CANARDS, INLETS
  - SERVICEABLE INSTRUMENTATION TRAY UPON REMOVAL OF FWD FUSELAGE SHELL
- WING PRESSURE TAPS (75)
  - ALL PRESSURE ROUTING IS INTERNAL TO MAIN WING VIA EDM/EB WELD FOR BETTER LINE FIDELITY (FLAP PRESSURES MUST BE SURFACE ROUTED)
  - TAP LOCATIONS
    - W.S. 50 LEFT WING: 16 TOP + RIGHT WING: 11 BOTTOM = 27
    - W.S. 114 LEFT WING: 33 TOP + RIGHT WING: 15 BOTTOM = 48
  - ONE 48 PORT ESP SERVICING EITHER W.S. 114 OR W.S. 50
- CANARDS AND VERTICAL TAIL
  - REPLACEABLE WITH OFF BLOCKS
  - NO CANARD REMOTE CONTROL
- TOLERANCES AND FINISH
  - HAND REFINEMENT ON WING L.E. (10% CHORD) TO .001 INCH } SURFACE FINISH 8-16 μINCH
  - REMAINDER OF WING AND CANARD: ± .004 INCH } SURFACE FINISH 8-16 μINCH
  - FUSELAGE: .006 INCH
- BALANCE
  - PROPOSED 1.75" NTF BALANCE TO BE BUILT BY NASA LaRC

This chart provides the same ready reference for discussing electronic instrumentation. It is noted that the specific information contained here was a direct result of the December 1981 working session at NASA Langley.

INSTRUMENTATION

- INSTRUMENTATION TRAY CARRYING:
  - 48 PORT ESP SENSOR W/DIGITAL ADDRESS PC BOARD
  - AOA SENSOR
- ELECTRICAL AND PNEUMATIC LINES FOR ABOVE UNITS
  - ELECTRONIC CONTROL LINES:

    (5) #20 AWG TEFLON INSULATED WIRE (TIW) - ONE EACH FOR GROUND +12V, -12V, $+V_S$, $-V_S$

    (8) #24 AWG TIW - ONE EACH FOR SIX ADDRESS LINES AND ONE EACH FOR THE TWO MODULE OUTPUT LINES
  - HEATER CONTROL LINES:

    (2) #20 AWG TIW - ONE EACH FOR HEATER POWER

    (3) #26 AWG TIW - ONE EACH FOR SENSOR LEADS
  - PNEUMATIC LINES

    (4) 0.060 I.D. NYLON TUBING - ONE EACH FOR C_1 LINE, C_2 LINE, CALIBRATE LINE, AND REFERENCE LINE
  - AOA SENSOR (ACCELEROMETER)

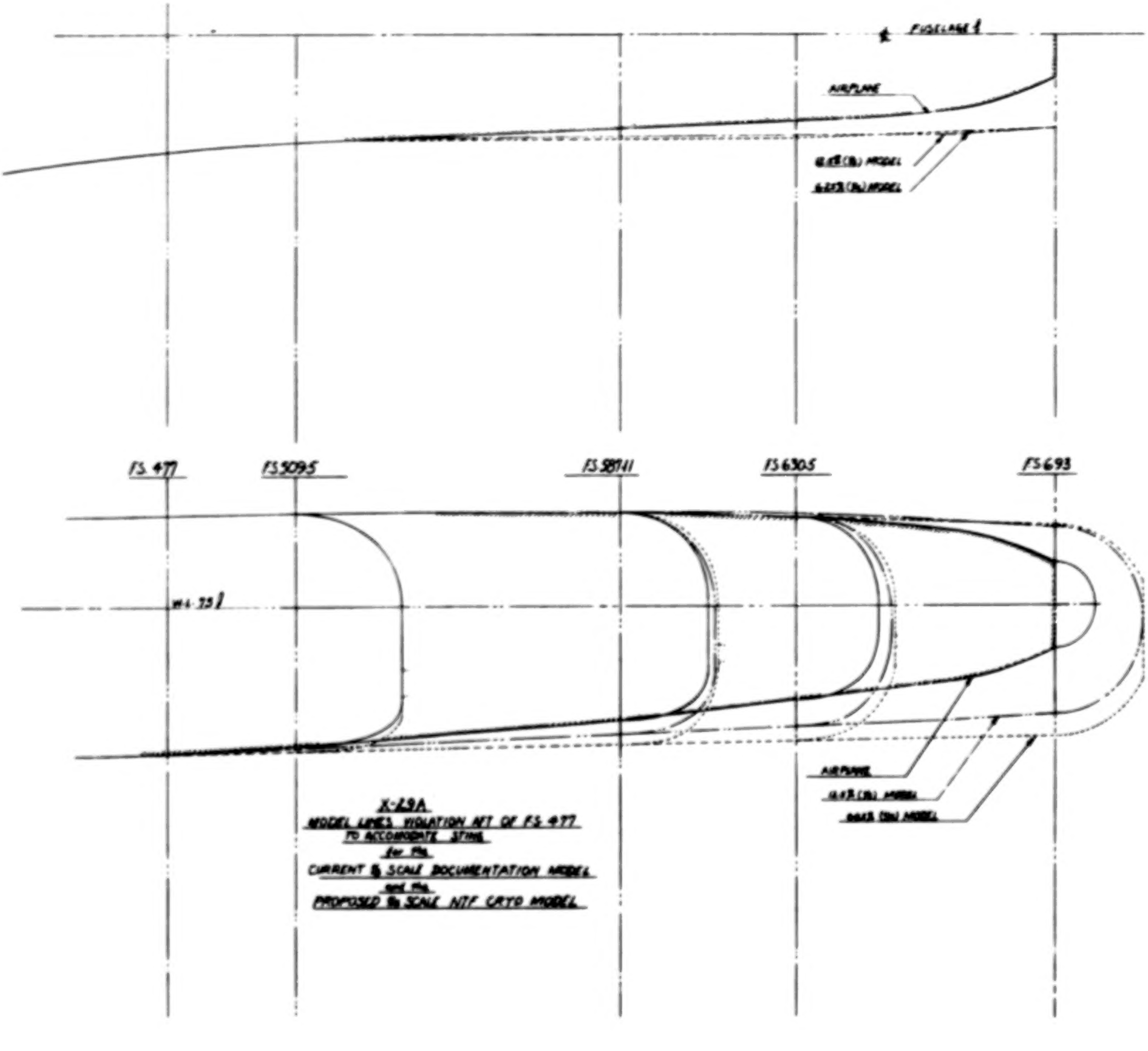
    (10) #26 AWG TIW (15 OR 20 WATTS; ½ AMP)
- THERMOCOUPLES - INTERNAL FUSELAGE: (3) TYPE K - CHROMEL/ALUMEL
- 1.75" NTF BALANCE: NF = 2500#, AF = 250#, SF = 1000#, PM = 5000 IN-LBS., YM = 2000 IN-LBS., RM = 1500 IN-LBS.

Since the X-29A air passage lines are frozen, this chart of configuration variables is limited to the preliminary selection of control surface position.

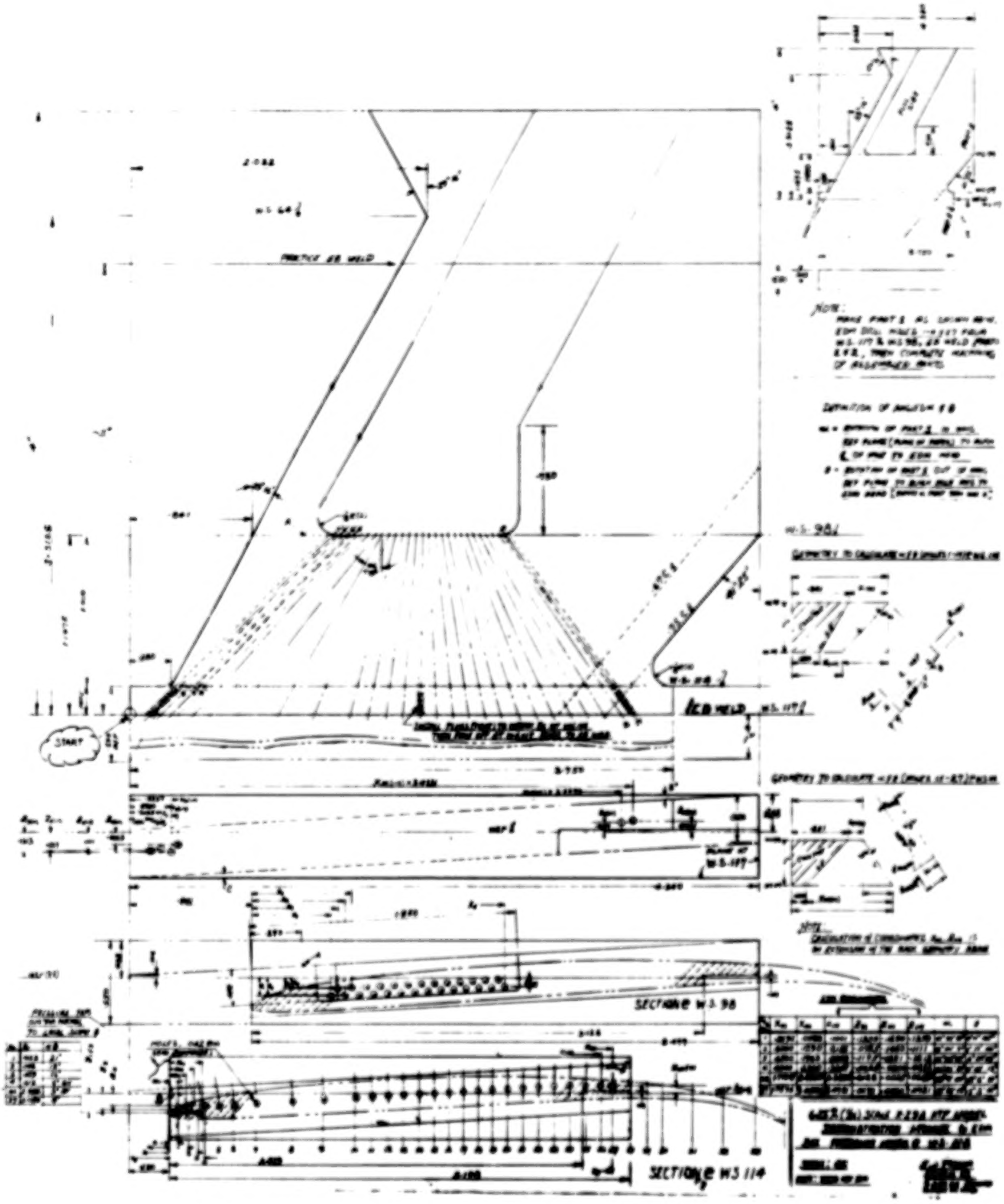
CONFIGURATION VARIABLES

- WING FLAPS: MANEUVER/CRUISE/SUPERSONIC/HI-α
- STRAKE FLAPS: (+/-) 5°, 10°, 30°
- CANARDS: 0°, +30°, -60° (ANY COMBINATION L&R)
- RUDDER: 0°, 10°, 20°, 30° (T.E. DEFLECTED RIGHT)
- VERTICAL TAIL, CANARDS, AND FLAP HINGE FAIRING: ON AND OFF

A comparison between aft airplane and NTF model air passage lines shows how the airplane lines must be modified to accommodate the model sting support. As a reference, the existing 12.5-percent scale Documentation Model is also shown. Since the NTF model aerodynamic loading can be relatively much higher than the Documentation Model (tested in air tunnels), the relatively larger sting for the NTF model causes the greater model lines violation.


FUSELAGE ℄
AIRPLANE
12.5% (1/8) MODEL
6.25% (1/16) MODEL
FS 477
FS 509.5
FS 588.41
FS 630.5
FS 693
WL 73 ℄
AIRPLANE
12.5% (1/8) MODEL
6.25% (1/16) MODEL
X-29A
MODEL LINES VIOLATION AFT OF FS 477
TO ACCOMODATE STING
for the
CURRENT 1/8 SCALE DOCUMENTATION MODEL
and the
PROPOSED 1/16 SCALE NTF CRYO MODEL

This is a detail of a portion of the X-29A model wing where the EDM process is applied to drill pressure passages in the middle of the wing for pressure orifices at wing station 114. The detail emphasizes the need for calcuation accuracy of the layout geometry to start an EDM drilled hole in one place and emerge in another place with virtually no deviation beyond a few thousanths of an inch. Before such an attempt to drill high-density pressure passages is started, the mathematics and machine operation set-up must be thoroughly checked and double-checked. (All specimens were fabricated by the Grumman PDOC organization under the direction of Rudy Ferro.)



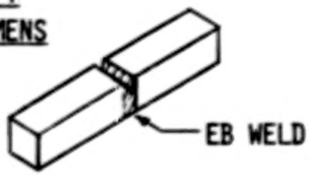
BEST DOCUMENT AVAILABLE

Presented here are the results of standard configured Charpy and tensile specimens of electron-beam-welded Vascomax material. Some of the Charpy specimens and all of the tensile specimens were welded in the as-received state, re-solution heat treated, and aged. The other Charpy's (5, 6, and 7) were only aged as shown. Those that were only aged had a reduced Charpy V-notch value, which shows that the re-solution heat treat cycle to improve grain structure should be the accepted process to improve material toughness. It is noted at this time that the lowest Charpy value of 17 ft-lb in specimens 1 to 4 compares favorably with those of the NASA Langley unwelded specimens recently tested.

RESULTS OF GRUMMAN EB WELDED VASCO MAX 200 TEST SPECIMENS

PERFORMED AT NASA LANGLEY ON MAY 4-5, 1982

CHARPY SPECIMENS

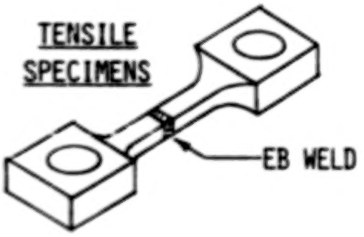


IMPACT TEST REPORT

MACHINE - SATEC SI-1C, CAPACITY: 240 FT-LB
IMPACT VELOCITY: 17 FT/SEC
SPECIMEN/TYPE: CVN SIZE: STANDARD

SP. NO.	TEST TEMP °F	IMPACT VALUE (FT-LBS)	LATERAL EXPANSION (MILS)	COMMENTS
1	-320	21	6	-ANNEALED @ 1500°F FOR ONE HOUR,**AIR COOLED -AGED @ 900°F FOR THREE HOURS;**AIR COOLED
2	-320	17	4	
3	-320	20	3	
4	-320	20	5	
5*	-320	5	7	AGED @ 900°F FOR THREE HOURS;**AIR COOLED
6	-320	14	3	
7	-320	15	3	
				*DEFECT IN WELD HOLE **IN AIR FURNACE

TENSILE SPECIMENS



SP.	TEST TEMP °F	FAILURE LOAD LB	NECK DOWN INCHES	FAILURE INCHES
A	-302	13000	.13	.20
B	-302	12790	.125	.198
C	-302	12720	.128	.206

NOTE:

1. SPECIMENS ANNEALED @ 1500°F FOR ONE HOUR,**AIR COOLED AND AGED @ 900°F FOR 3 HOURS, AIR COOLED.
2. SPECIMENS WERE PREDICTED TO BREAK AT 12,000 LB BASED ON 250,000 PSI ULTIMATE STRESS AT ~ -300°F AND MIN-CROSS SECTION OF .248X.1935 SQUARE INCHES.

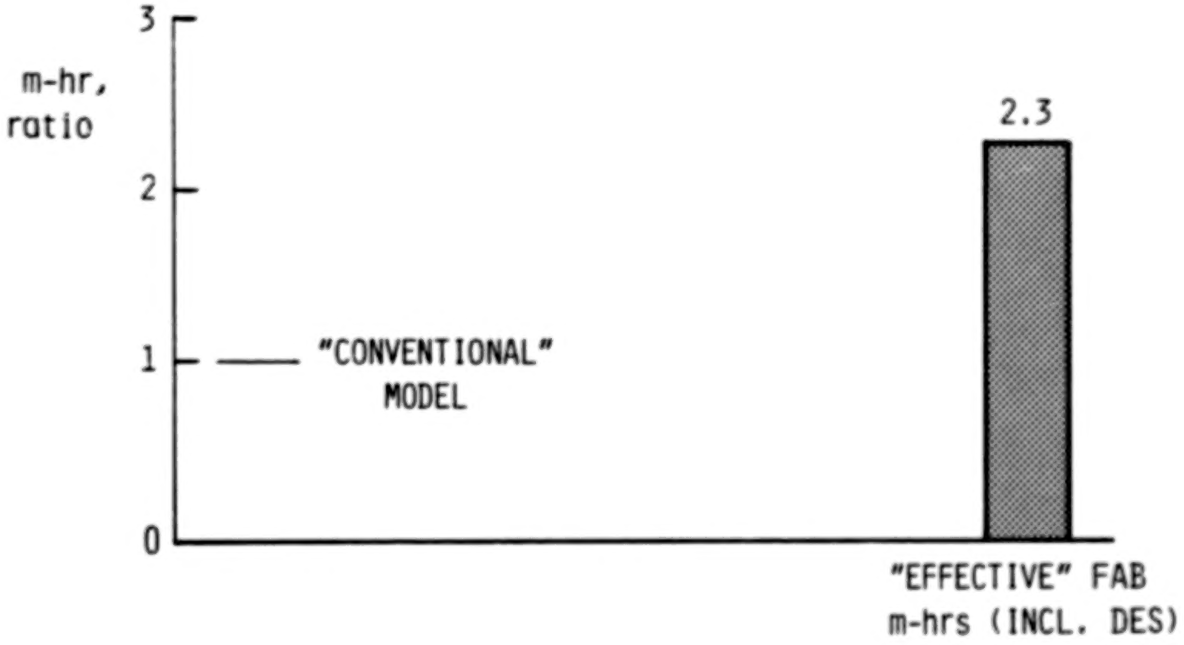
PART III

COST AND SCHEDULES

G. DaForno

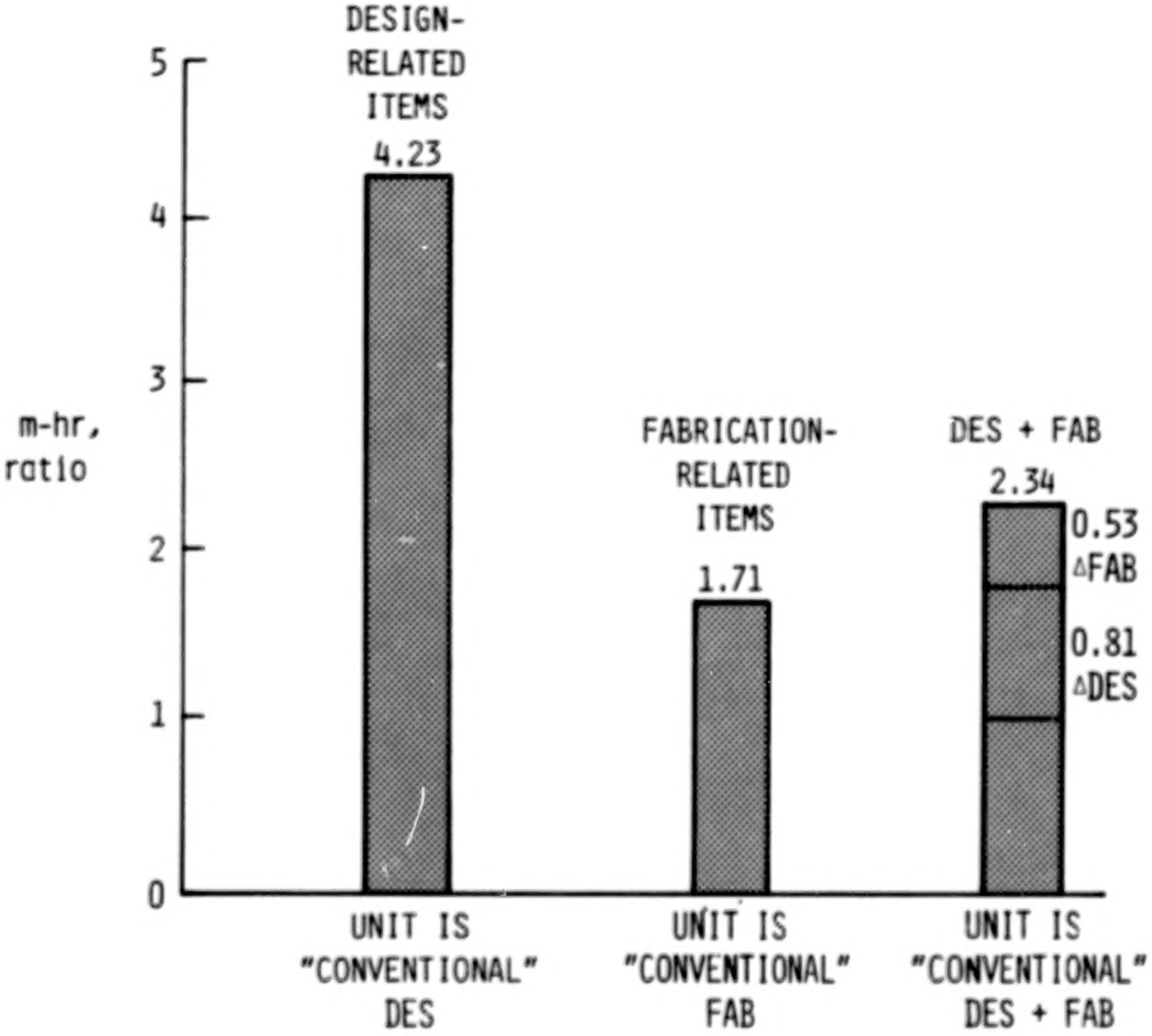
On costs, we give first the 'bottom line'; that is, the answer to the question "How much more does this NTF model cost than the same-size 'conventional' model?" The best way to give the answer is in the form of man-hour ratios. (These man-hours are for design and fabrication; however, design hours cost considerably more (say, 1.375 times) than fabrication hours, and hence are not cost additive to fabrication hours. To get comparable man-hour ratios and cost ratios, the design man-hours have been translated into 'effective' fabrication hours by multiplying them by 1.375.)

RELATIVE COST OF DESIGN AND FABRICATION
OF X-29A 1/16 NTF MODEL (EST.)



The man-hour ratio can be broken down into the two traditional elements, design and fabrication, each given as a ratio to the corresponding 'conventional' effort. (We prefer a breakdown into two elements rather than four - design, fabrication, NC programming, and computer costs.) This figure shows the very considerable increase we envision in the design effort.

RELATIVE COST BROKEN DOWN INTO RELATIVE DESIGN AND RELATIVE FABRICATION COSTS



Every cost estimate depends heavily on precisely what is costed and what ground rules are used. This chart spells out key information of this nature associated with the estimates of the previous charts. The estimate of the NTF model was considerably detailed, even if at a model concept level. The requirements set forth in LHB 8850.1, Wind Tunnel Model Systems Criteria (Langley Research Center, Sept. 1981), were addressed in intent but were not followed to the letter. These criteria were interpreted by Grumman's quality assurance and quality control disciplines, since a major airframe manufacturer would be conditioned in attitude by the tradition of full-scale production hardware.

GROUND RULES
FOR DES & FAB COST OF X29A 1/16 NTF MODEL

- CONVENTIONAL MODEL:
  - CONVENTIONAL SIZE FOR 8 FT TRANSONIC TUNNEL (USABLE ALSO AT HIGH α IN 7' x 10's)
  - MODERATE MAC RE, $\sim 3 \times 10^6$, STEEL WING
  - NO LE HAND REFINEMENTS, CURSORY INSPECTION
  - NO DEFLECTION TEST
  - COST IS STATISTICAL
- NTF MODEL
  - WORK PACKAGE FROM 'REQUIREMENTS' TO 'END PRODUCT'
  - END PRODUCT: COMPLETE MECHANICAL ASSEMBLY AT GRUMMAN READY FOR WIRE INSTALLATION & CALIBRATION AT NASA LaRC
  - COST ITEMS NOT INCLUDED
    - + VASCOMAX 200 (BUT ACCEPTANCE CERTS INCLUDED)
    - + STING & KNUCKLES (DES & FAB)
    - + ESP
    - + TRAVEL EXPENSES
  - COST ITEMS INCLUDED: FULL DOCUMENTATION OF EFFORT, SYSTEMATIC LIAISON WITH NASA LaRC & COST TRACKING
  - COST IS BUDGETARY ESTIMATE OF THE ITEM-BY-ITEM BUILD-UP TYPE
  - REASONABLY-DEFINED SCOPE OF 22 TASKS

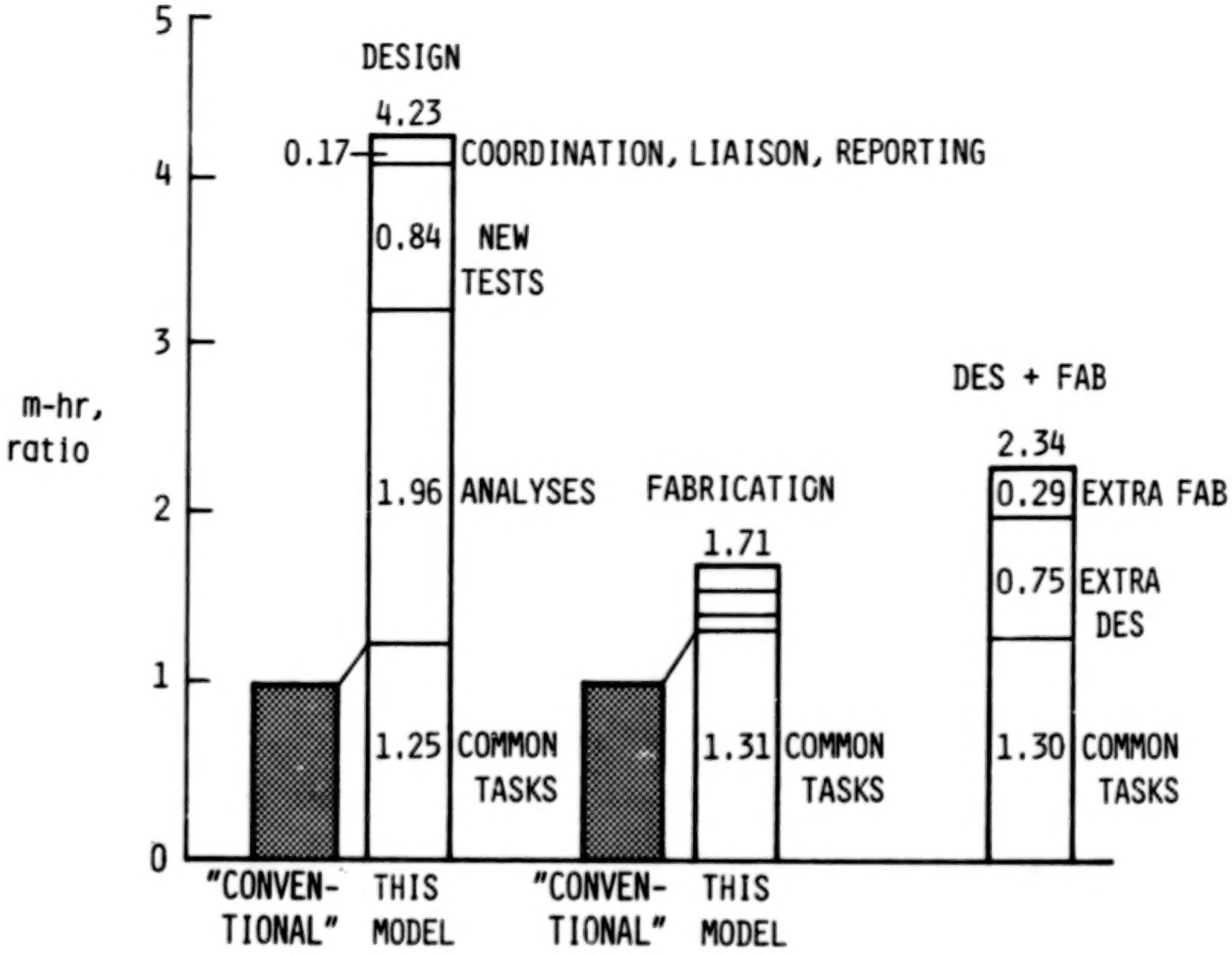
To cost out the NTF model, the design and fabrication effort was broken down into the work items listed in this figure. We separated the 'conventional' work items (requiring perhaps a small increase in effort in the case of the NTF model) from the new, NTF-required ones.

COST BUILD-UP
FOR DES & FAB OF THE NTF MODEL

	1.	CONVENTIONAL MODEL DESIGN AND STRESS ANALYSIS	DES
*	2.	SPECIALIST SUPPORT (STRESS AND THERMO)	
	3.	MODEL LINES	
*	4.	DETAILED STRESS ANALYSIS (INCL. FINITE ELEMENT ANAL.)	
*	5.	FRACTURE MECHANICS ANALYSIS	
*	6.	THERMAL ANALYSIS	
*	7.	DIVERGENCE ANALYSIS (COMPLETE MODEL SYSTEM)	
*	8.	FLUTTER ANALYSIS (THEORETICAL)	↓
*	9.	MATERIAL QUALITY ASSURANCE (CRYO USE) (INCLUDING CHARPY V-NOTCH AND TENSILE SPECIMENS)	FAB
	10.	FABRICATION AND INSTRUMENTATION (PRESSURE TAPS)	
	11.	INSTRUMENTATION (ELECTRONICS)	
	12.	INSPECTION	↓
*	13.	STATIC TEST FOR DEFLECTION	DES
*	14.	INFLUENCE COEFF. TEST	
*	15.	GROUND VIBRATION SURVEY & FLUTTER ANALYSIS	
*	16.	MODEL ENVELOPE	↓
*	17.	HAND REFINEMENTS	FAB
	18.	AERO TEST ENGINEERING (DES SUPPORT)	DES
	19.	AERO/L&D/PROJECT (DES SUPPORT)	↓
	20.	PROGRAM MGMT SERVICES	DES & FAB
*	21.	COORDINATION	
*	22.	LIAISON WITH NASA & REPORTS	↓

* SPECIAL REQ. FOR NTF

The work-item breakdown and the associated costs give some insight as to where the increased costs of the NTF model are accumulated. This is the point of this figure: in our estimates, a very large contributor to the increased design cost is detailed analysis and the tests in support of this analysis. This new activity is sufficient to shift the design versus fabrication balance on conventional models (1/4 versus 3/4) toward a different level (almost 1/2 veruss 1/2)/



This figure is a summary of the key points touched upon in the three parts of the paper (requirements, design and fabrication concept, and cost and schedule). (A detailed layout of the schedule, not presented, shows that at least 15 months are needed from the start of the concept work to delivery of the complete mechanical assembly of the model, ready for electronic instrumentation installation and test-site pretest activities.)

SUMMARY (X29A NTF MODEL CONCEPT)

REQUIREMENTS AND GUIDELINES/DESIGN LOADS

- ALL DATA ACCOMMODATED--AERO (HIGH SPEED AND HIGH α), LOADS, CORRELATION WITH 3 KEY TUNNELS
- MIN DESIGN LOAD AND LOWEST TEMPERATURES:
  $(c_N q)_{DES}$ = 2700 PSF, N = 1950#, T_t = 85 K
- MODEST q STUDY POSSIBLE (Δq = 1000 PSF, AT MDP)

DES AND FAB CONCEPT

- VASCOMAX 200
- MONOCOQUE CONSTRUCTION/EB WELDS/MIN MECHANICAL JOINTS
- EDM PRESSURE PASSAGES; 75 TAPS ACCOMMODATED ON WINGS
- DEMO OF EDM AND EB WELD FEASIBILITY
- INSULATED CAVITY FOR ESP (ESTIMATED HEATER POWER OK)

COST AND SCHEDULE

- DES AND FAB OF THIS NTF MODEL IS ~ 2.3 TIMES CONVENTIONAL
- DES IS ~ 4.2 TIMES CONVENTIONAL DES
- FAB IS ~ 1.7 TIMES CONVENTIONAL FAB (± 20%)
- COMPRESSED SCHEDULE: 15 MONTHS, INCLUDING CONCEPT

PART IV

QUESTIONS PRESENTED AT PANEL DISCUSSION

Cryogenic Charpy values of about 25 ft-lb have been informally mentioned as a typical requirement for NTF models. The model concept presented in this paper relies on Vascomax 200 in slab form, a heat treatment of 3 hours at no greater than 900°F, EB welding as demonstrated in the specimen data shown, and stresses of 200 ksi at -320°F. There is little point in investing more resources in the concept if a 25-ft-lb requirement is judged to be essential. Hence the question in this figure was posed to panel and audience.

ACCEPTABILITY OF VASCOMAX 200 (AGED 3 HOURS, 900°F) FROM TOUGHNESS STANDPOINT

- SUPPOSE THAT CRYO CHARPYS COME OUT ON THE ORDER OF 17
- IS THE CONSENSUS OF THIS TECHNICAL GROUP THAT THE MATERIAL IS ACCEPTABLE FOR MODEL CONDITIONS -320°F, 200 KSI?

Sting dynamics has been a traditional, unpredictable, and dangerous limitation to high Reynolds number/high q testing into incipient stall and stall proper at low and transonic speeds. For such testing in the NTF, we think that real-time monitoring of sting dynamics is unavoidable.

STING DYNAMICS AT HIGH α, LOW-SPEED/REAL-TIME MONITORING OF STRUCTURAL INTEGRITY (S.I.)

- WHAT ARE THE NTF REQUIREMENTS TODAY TO MONITOR S.I.?
- WHAT DO YOU SUGGEST BE DONE ON THIS ITEM FOR TACTICAL CONFIGURATION MODELS?
- ANY IDEAS BESIDES STRAIN GAGES? CAN THE TIME-DEPENDENT BALANCE OUTPUT SOMEHOW BE USED?

It has been informally proposed to use Vascomax 200 that has been re-solution heat treated (annealed) to refine the grain structure with no further aging cycle, in order to try to realize a better than 17 ft-lb Charpy V-notch value. Although the Charpy value will be improved, the strength will only increase to possibly 150 ksi at -320°F. (This strength may be generally unacceptable since an aging cycle will yield a desirable approximately 205 ksi at room temperature and nearly 270 ksi at cryogenic temperature.)

The point of these questions was to sound out the panel and audience on this idea, since one corollary of it is particularly attractive for the X-29A model concept, as follows. Two fuselage halves initially undergo a re-solution heat treatment and aging cycle, after which the pressure tubings are inserted and finally the halves are EB welded together, since this particular welding is in a low-stress area. The heat-affected zone in welding the two halves together would be less than 0.10 in. in this low-stress area. Re-aging at this point exposes the tubing to 900°F and it would be attractive in our case to eliminate the second aging cycle.

FEASIBILITY OF ELIMINATING AGING TREATMENT OF VASCOMAX 200

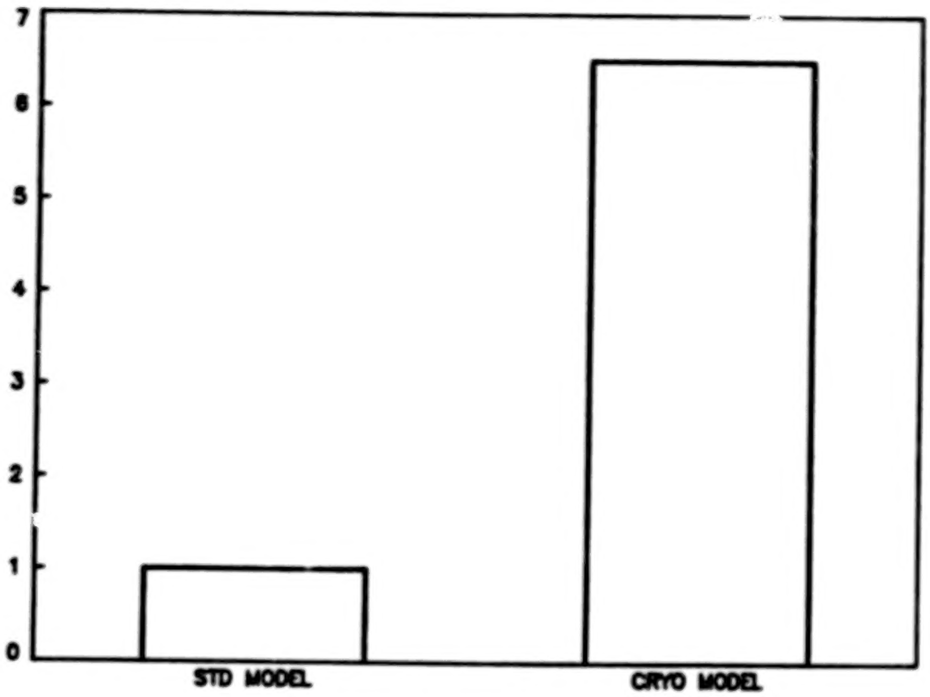
- INTENDED USE: -320^{O}F/200 KSI; ALSO NTF-AIR
- IS THE CONSENSUS OF THIS TECHNICAL GROUP THAT THIS ISSUE MAY BE FEASIBLE AND WORTHWHILE TO EXPLORE?
- IF CONSENSUS IS YES, WILL ANYONE DO THE TESTS IN THE NEXT FEW MONTHS?

COST FACTORS FOR NTF MODELS

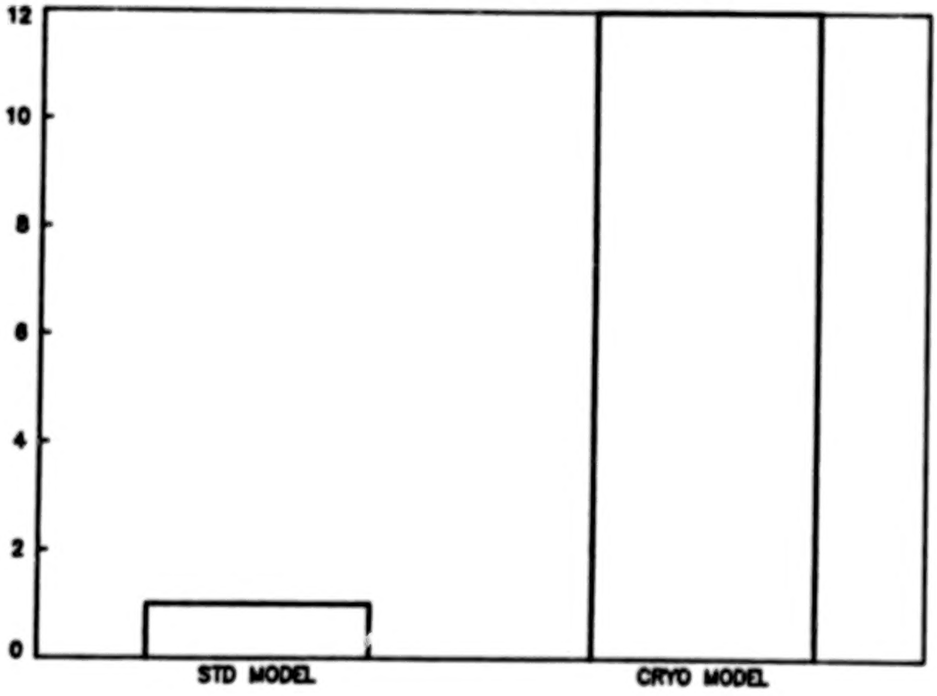
William C. Whisler
The Boeing Company
Seattle, Washington

This presentation will discuss items that make the design of cryogenic models more expensive, including materials, increased thoroughness, and extensive design. Other sources of this increase are greater shop costs due to higher tolerances, more numerically controlled programming time, and more care in machining. Charts are presented of the relative costs of cryogenic and standard-force models. It is concluded that relative costs will drop as experience is gained.

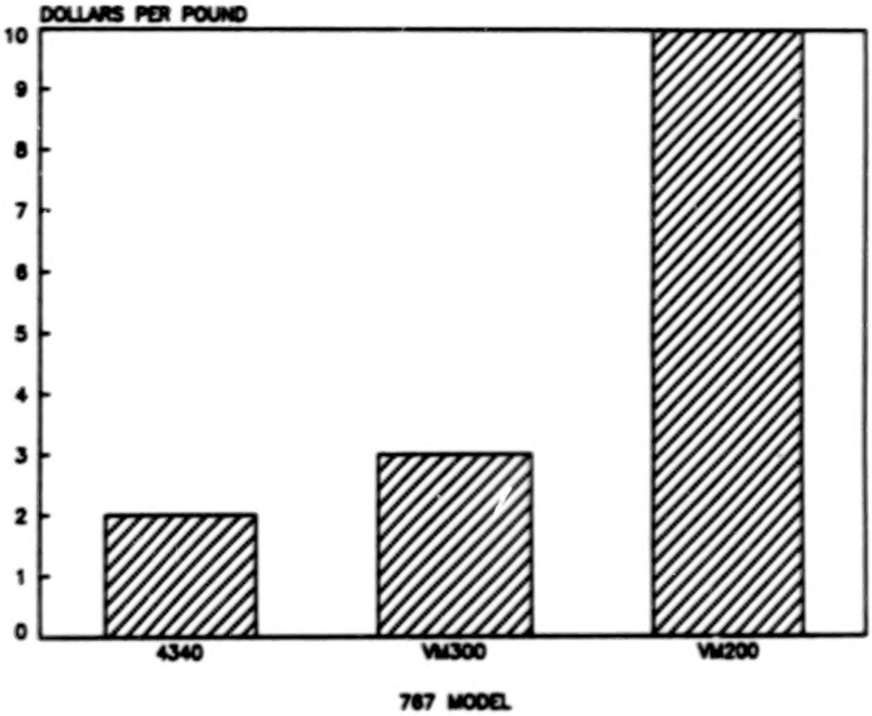
RELATIVE PROGRAMMING COSTS



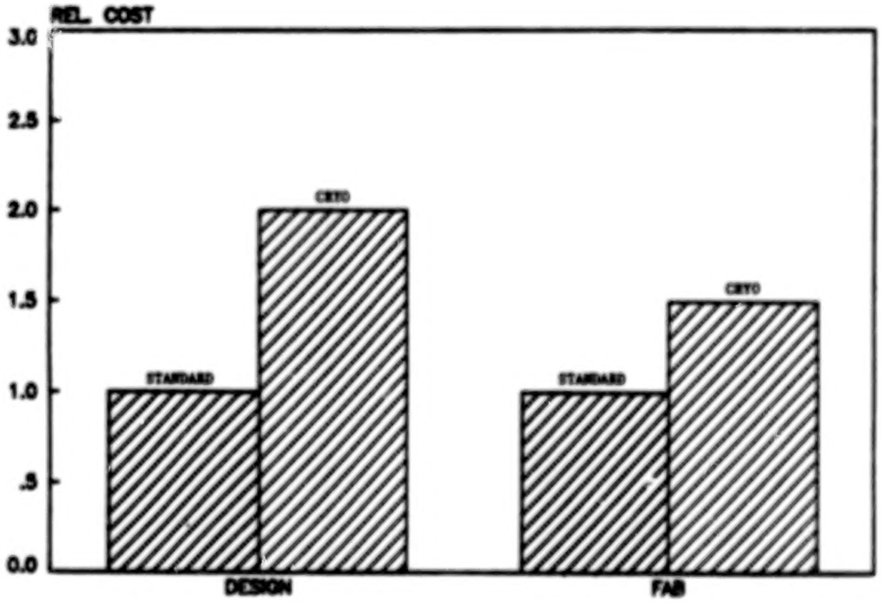
RELATIVE COMPUTER RESOURCE UNITS



MATERIALS COST



RELATIVE COSTS
STANDARD MODEL VS CRYO MODEL



ENGINEERING AND FABRICATION COST CONSIDERATIONS FOR CRYOGENIC WIND TUNNEL MODELS

Richard M. Boykin, Jr., and Joseph B. Davenport, Jr.
NASA Langley Research Center
Hampton, Virginia

DESIGN

To date NASA Langley has very little real experience on which to base an objective comparison of cryogenic wind tunnel model costs versus conventional model costs. Most of the experience gained over the past year or two contains significant development costs, such as material characterizations, developmental testing to understand the effects of the cryogenic environment on subsystems, and additional analyses that would not normally be required. This discussion, then, presents a more philosophical look at the main cost drivers, and considers primarily models for the National Transonic Facility (NTF). Both design or engineering costs and fabrication or manufacturing costs will be addressed.

Models for NTF testing are basically characterized by high-precision requirements, such as operation in an extremely low temperature environment and under relatively high loads. These are not new to model design individually, but collectively they require additional and special considerations. The requirement for high precision in terms of surface finish and tolerances adds very little to the engineering or design costs, but may be a significant factor in the manufacturing manpower or cost.

The cryogenic temperatures require the use of materials with relatively high fracture toughness but at the same time high strength. Some of these materials are very difficult to machine, requiring extensive machine hours which can add significantly to the manufacturing costs. Some additional engineering costs will be incurred to certify the materials through mechanical tests and nondestructive evaluation (NDE) techniques, which are not normally required with conventional models because of the high safety factors and insensitivity to flaws or cracks when operating at normal temperatures. When instrumentation such as accelerometers and electronically scanned pressure (ESP) modules is required, temperature control of these devices will have to be incorporated into the design, which will require added effort. Additional thermal analyses and subsystem tests may be necessary, which will also add to the design costs.

The largest driver to the design costs is potentially the additional static and dynamic analyses that will be required to insure structural integrity of the model and support system. The depth of analysis, and therefore the cost, will be a function of the margins of safety existing in the hardware. A handbook approach should first be used to examine the problem, and if high margins are indicated then additional analyses may not be required.

In summary, the largest impact to the design costs of cryogenic or NTF models is due to the analyses required to obtain confidence in the design. The tendency in the early stages of developing such models is to take a conservative approach. As more experience is gained and better analysis techniques are developed, these costs should come down.

FABRICATION

In general, the discussion given herein is valid for any wind tunnel model for the cryogenic transonic high Reynolds number tunnel. This is not to say that models for the National Transonic Facility will not cost more than models for conventional transonic tunnels; rather, the cost factors for the two classes of models are the same. The major cost factors for wind tunnel models are model complexity, tolerances, surface finishes, materials, material validation, and model inspection. To provide the maximum influence on model cost, it has been found that fabrication personnel should be involved early in the design process. Manufacturing processes must be determined in advance and attention must be directed toward processes that induce minimum stresses in the metal components. Since there will be a variety of types of models, the cost of cryogenic model fabrication must be determined on a case-by-case basis.

ENGINEERING COST CONSIDERATIONS

- LITTLE REAL EXPERIENCE EXISTS
  - EXPERIENCE TO DATE INCLUDES SIGNIFICANT "DEVELOPMENT" COSTS
- WHAT ARE PRIMARY COST DRIVERS AFTER DEVELOPMENT WORK IS DONE?

CRYO MODEL CHARACTERISTICS

- NTF MODELS CHARACTERIZED BY:
  - HIGH PRECISION
  - CRYO TEMPERATURES
  - HIGH LOADS
- NOT NEW TO MODEL DESIGN - INDIVIDUALLY
- COLLECTIVELY - CREATE SOME SPECIAL CONSIDERATIONS

FACTORS AFFECTING THE INCREASE IN NTF MODEL COST AS COMPARED TO CONVENTIONAL MODEL COST (Δ COST)

- PRECISION - TOLERANCE & SURFACE FINISH
  - MINOR DESIGN COST FACTOR
  - SIGNIFICANT FABRICATION COST FACTOR
- CRYO TEMPERATURES
  - MATERIALS
    - SPECIAL MATERIALS REQUIRED - STRENGTH, STABILITY, FRACTURE TOUGHNESS
    - ENGINEERING COSTS - MINOR
    - CAN BE SIGNIFICANT FABRICATION COST FACTOR
  - INSTRUMENTATION
    - ESPs, ACCELEROMETERS - TEMPERATURES NEED TO BE CONTROLLED
    - ADDITIONAL EFFORT - DESIGN, ANALYSIS, TEST - MAY BE REQ'D
- HIGH LOADS
  - GENERALLY MORE DETAILED ANALYSES REQUIRED
  - DEPTH OF ANALYSIS DETERMINES COST
  - DEPTH REQUIRED IS FUNCTION OF FACTOR OF SAFETY
  - USE HANDBOOK APPROACH TO DETERMINE IF PROBLEM EXISTS AND FURTHER ANALYSIS IS REQUIRED

SUMMARY

- LARGEST POTENTIAL ENGINEERING Δ COST OCCUR IN THE STATIC AND DYNAMIC ANALYSES REQUIRED TO OBTAIN CONFIDENCE IN DESIGN.
- SHOULD ONLY REPRESENT SIGNIFICANT Δ COSTS WHEN FACTORS OF SAFETY ARE LOW.
- EACH MODEL IS DIFFERENT - CAN'T GENERALIZE.
- FREQUENT COMMUNICATION IS IMPORTANT TO KEEP COSTS DOWN.

MANUFACTURING COST FACTORS

- COMPLEXITY OF MODEL
- TOLERANCES
- SURFACE FINISHES
- INSTRUMENTATION
- MATERIALS
- SPECIAL PROCESSING
- QUALITY ASSURANCE REQUIREMENTS

COMPLEXITY OF MODEL

- CONSTRUCTION METHOD
  - A. UNITIZED
  - B. STRONG BACK
- SHAPE AND ASPECT RATIO OF AIRFOIL.
- NUMBER OF INTERCHANGEABLE ELEMENTS; FLAPS, SLATS, ETC.
- TYPE, NUMBER, INSTALLATION METHOD, AND ROUTING OF INSTRUMENTATION.
- COVERPLATES AND ACCESS HATCHES TO INSTRUMENTATION.
- ATTACHMENT METHODS FOR CONTROL SURFACES.

TOLERANCES - AIRFOIL SECTIONS

- TOLERANCE AND SURFACE FINISH MUST BE CONSIDERED JOINTLY TO DETERMINE MANUFACTURING COSTS.

- TIME REQUIRED TO MACHINE AND HANDWORK TO A GIVEN TOLERANCE INCREASES PROPORTIONALLY TO THE INCREASE IN TOLERANCE REQUIREMENT.

- FACTORS INFLUENCING COST OF ACHIEVING SPECIFIC TOLERANCE

  A. STABILITY OF MATERIAL

  B. MACHINING AND FINISHING METHOD

  C. PROPORTIONAL AMOUNT OF HAND FINISHING VERSUS MACHINE TIME

  D. REQUIRED SURFACE FINISH OF COMPLETED COMPONENT

SURFACE FINISHES - AIRFOIL SECTIONS

- TOLERANCE AND SURFACE FINISH MUST BE CONSIDERED JOINTLY TO DETERMINE MANUFACTURING COSTS.

- TIME REQUIRED TO MACHINE AND HANDWORK TO A GIVEN SURFACE FINISH INCREASES GEOMETRICALLY TO THE INCREASE IN FINISH QUALITY.

- FACTORS INFLUENCING COST OF ACHIEVING SPECIFIC SURFACE FINISH:

  A. FINISHING QUALITY OF MATERIAL

  B. MACHINING AND FINISHING METHODS

  C. PROPORTIONAL AMOUNT OF TIME REQUIRED FOR HANDWORK VERSUS MACHINE WORK

  D. REQUIRED TOLERANCE OF FINISHED COMPONENT

MATERIALS

- o COST OF MATERIALS
- o SPEEDS AND FEEDS
- o MANUFACTURING SEQUENCE
- o EQUIPMENT AND TOOLING

FABRICATION COST COMPARISON OF THREE TWO-DIMENSIONAL CRYOGENIC AIRFOILS OF SIMILAR DESIGN

MODEL	% THICKNESS	MATERIAL	FABRICATION COSTS IN MANHRS.	FABRICATION COST INCREASE	FACTORS IN INFLUENING COST INCREASE	% OF COST INCREASE BY FACTOR
#1	12%	15-5 S.S.	862	-	-	-
#2	14%	13-8 MO	948	10%	● QUALITY ASSURANCE	6%
					● CRYOCYCLING OF MATERIAL DURING FABRICATION	4%
#3	12%	VASCOMAX-200	1172	36%	0 INCREASED MACHINING TIME DUE TO MATERIAL AND INCREASED NUMBER OF OPERATIONS	21%
					0 QUALITY ASSURANCE	11%
					0 CRYO CYCLING OF MATERIAL DURING FABRICATION	4%

SUMMARY

- FABRICATION COST DRIVERS
  - A. COMPLEXITY OF MODEL
  - B. TOLERANCES AND SURFACE FINISHES
  - C. MATERIALS
  - D. INSPECTION AND VALIDATION
- DESIGN/ANALYSES, FABRICATION AND TESTING COSTS MUST BE EVALUATED JOINTLY TO DETERMINE MOST COST EFFECTIVE APPROACH.
- MODEL FABRICATION PERSONNEL SHOULD BE INVOLVED EARLY IN DESIGN STAGE TO PROVIDE MAXIMUM COST EFFECTIVE INFLUENCE.
- COST OF CRYOGENIC MODEL FABRICATION MUST BE DETERMINED ON A CASE BY CASE BASIS DUE TO VARIETY OF COST INFLUENCING FACTORS.
- MANUFACTURING PROCESSES MUST BE DETERMINED IN ADVANCE AND ATTENTION MUST BE DIRECTED TOWARD PROCESSES THAT INDUCE MINIMUM STRESSES IN METAL COMPONENTS.

DIMENSIONAL STABILITY CONSIDERATIONS FOR CRYOGENIC METALS

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Southampton, England

This presentation is a report on work performed as part of an effort to identify and where possible separate out some of the factors that contribute to dimensional stability in cryogenic wind tunnel models. Small dimensional changes in wind tunnel models being tested at high Reynolds number become quite significant because of the more stringent requirements on model aerodynamic coordinates and surface smoothness.

Initial problems were encountered with two-dimensional models made of 15-5 PH stainless steel, which warped significantly after being subjected to cryogenic testing in the 0.3-Meter Transonic Cryogenic Tunnel (TCT). Subsequently, an effort was undertaken to investigate the mechanisms that could cause model warpage during cryogenic testing.

The two basic mechanisms that can lead to warpage are (1) metallurgical structural instability in which one phase transforms partially or fully into a second phase which has a different crystal structure and volume, and (2) deformation due to the creation, or relief, of unbalanced induced or residual stresses. In the case of the 15-5 PH airfoils, it is highly probable that metallurgical instability was responsible for most of the observed warpage.

A major point to be made is that even in metallurgically stable materials, cryogenic cycling can alter the residual stress system and thus lead to dimensional changes. It is often possible, however, to achieve dimensional stability by carrying out a number of cryogenic cycles such that the stress system is stabilized and no warpage occurs during subsequent cycles.

A particular specimen configuration was established for use in the systematic evaluation of the factors influencing warpage and is shown in figure 1. Preliminary studies of a specimen made of VASCOMAX 200 suggest the possibility of manipulating the stresses in the surface layers by appropriate combinations of milling and grinding steps. This opens up the possibility of correcting or establishing the required surface profile of an airfoil. This behavior is illustrated in figures 2 and 3 which show the results of deflection measurements made after each machining step.

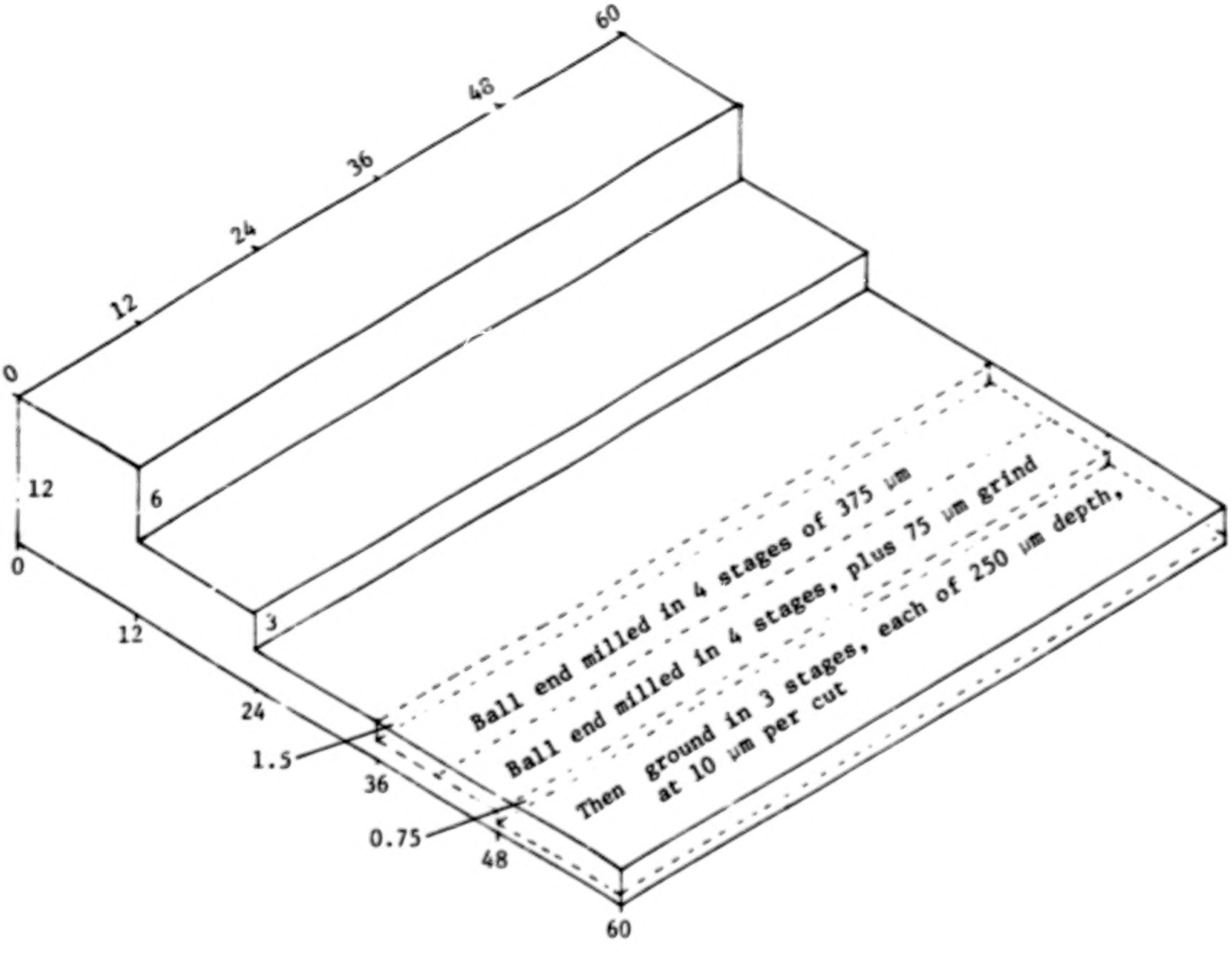

60
48
36
24
12
0
12
6
0
3
12
24
1.5
36
0.75
48
60
Ball end milled in 4 stages of 375 µm
Ball end milled in 4 stages, plus 75 µm grind
Then ground in 3 stages, each of 250 µm depth,
at 10 µm per cut

Figure 1.- Recommended configuration of proposed standard specimen for warpage experiments. (Dimensions in millimeters.)

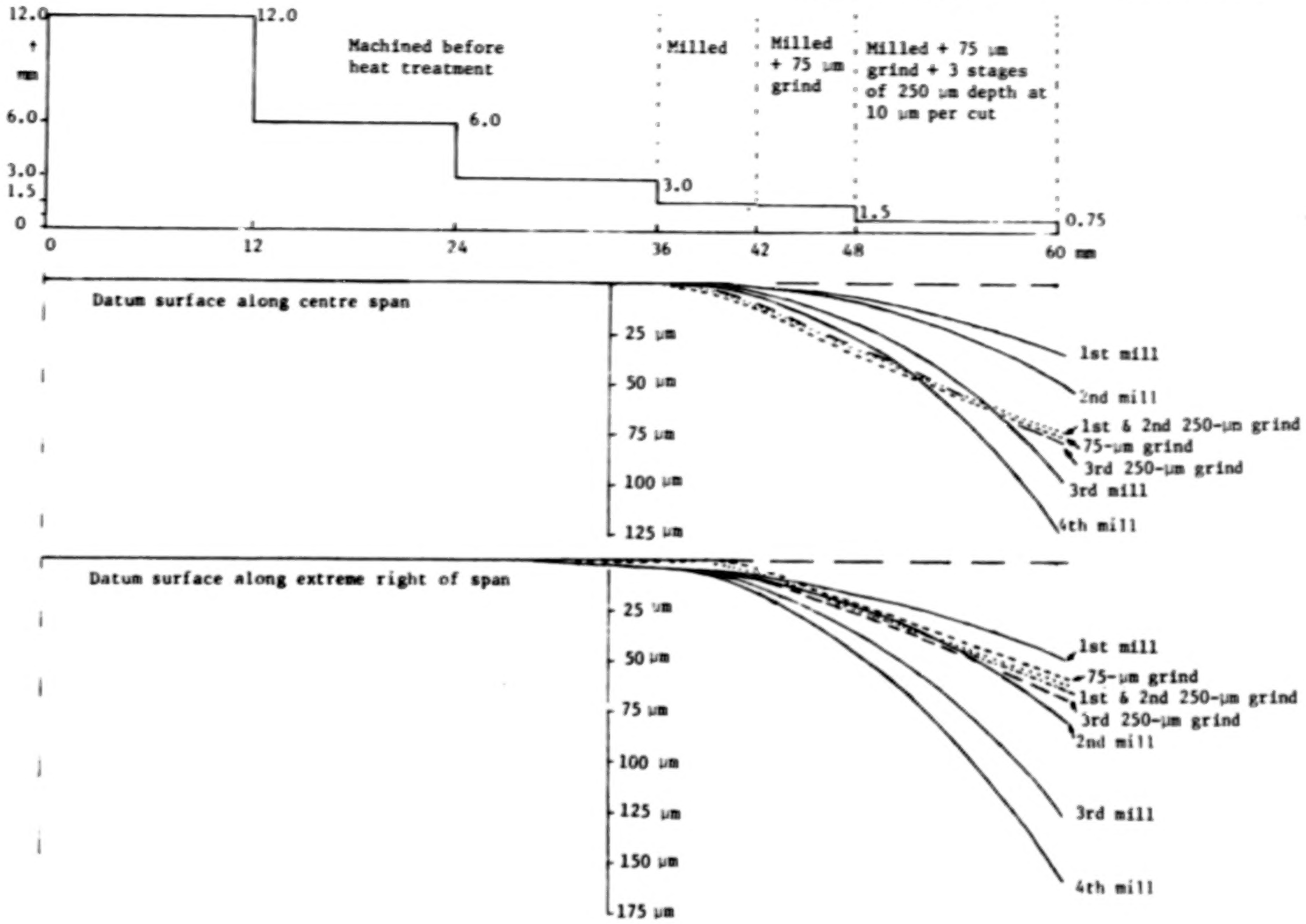


Figure 2.- Longitudinal profiles of machined Vascomax 200.

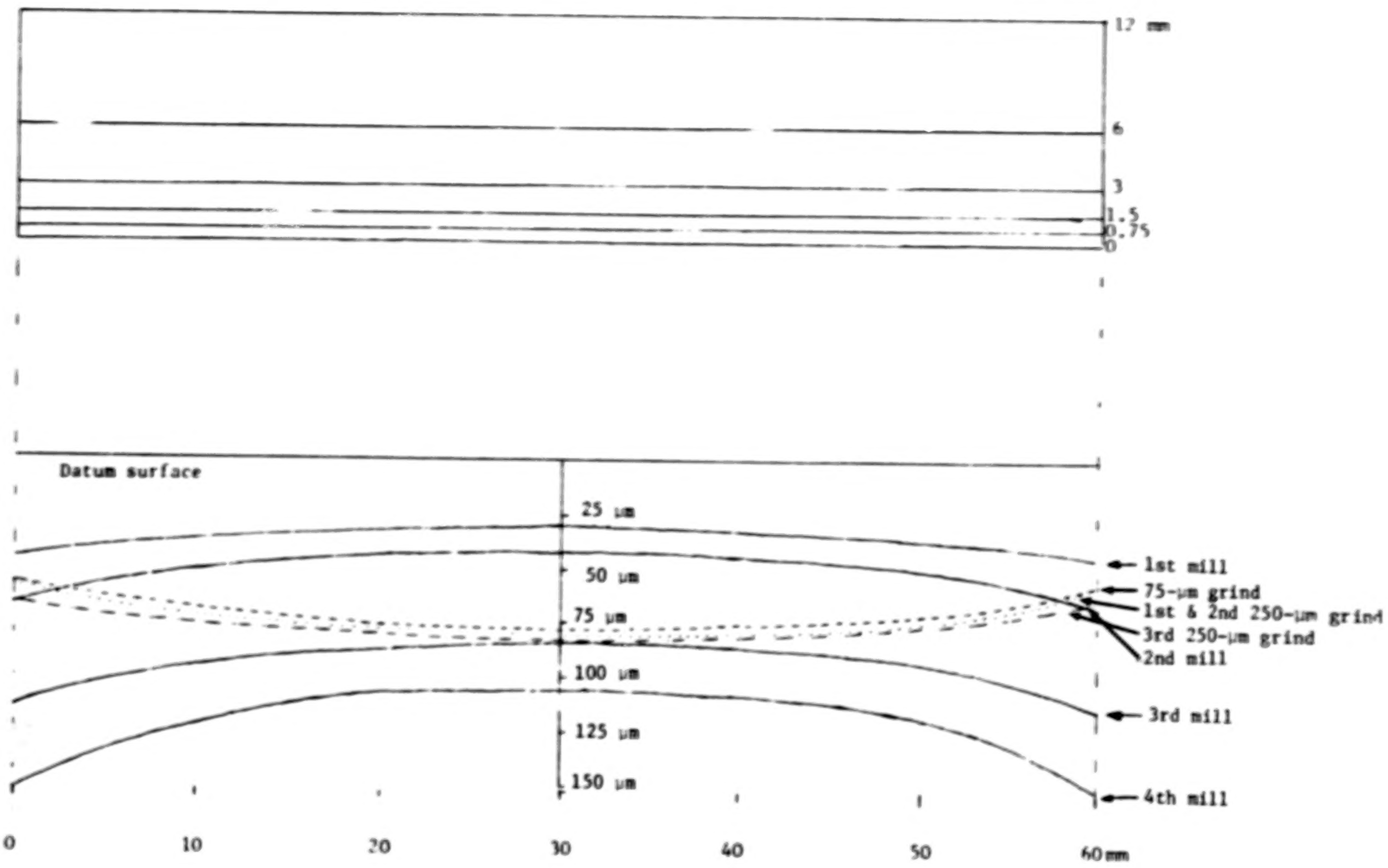


Figure 3.- Transverse profiles of machined Vascomax 200.

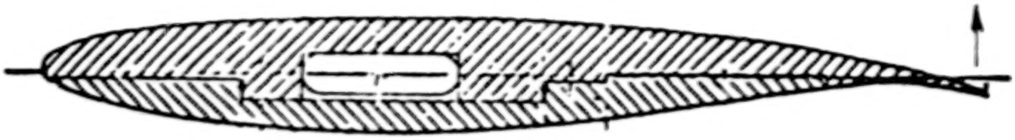
METALLIC ALLOY STABILITY STUDIES

George C. Firth
Lockheed-Georgia Company
Marietta, Georgia

An investigation into the dimensional stability of candidate cryogenic wind tunnel model materials was initiated due to the distortion of an airfoil model during testing in the Langley 0.3-Meter Transonic Cryogenic Tunnel. Flat specimens of candidate materials were fabricated and cryo-cycled to assess relative dimensional stability. Existing 2-dimensional airfoil models as well as models in various stages of manufacture were also cryo-cycled. The tests indicate that 18 Ni maraging steel offers the greatest dimensional stability and that PH 13-8 Mo stainless steel is the most stable of the stainless steels. Testing of more sophisticated "stepped" specimens will provide a basis for more conclusive comparisons.

Dimensional stability is influenced primarily by metallurgical transformations (austenitic to martensitic) and manufacturing-induced stresses. These factors can be minimized by utilization of stable alloys, refinement of existing manufacturing techniques, and incorporation of new manufacturing technologies.

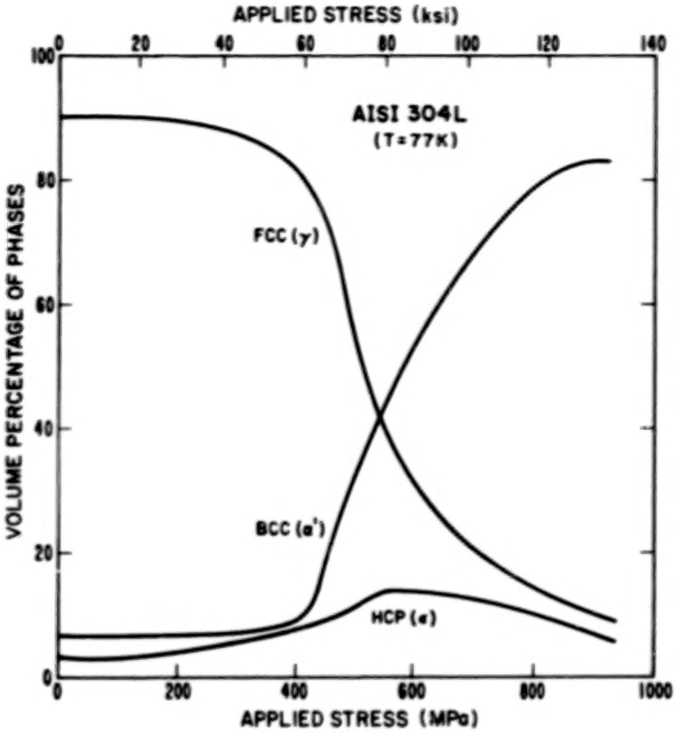
2-D AIRFOIL



DISTORTION MECHANISMS

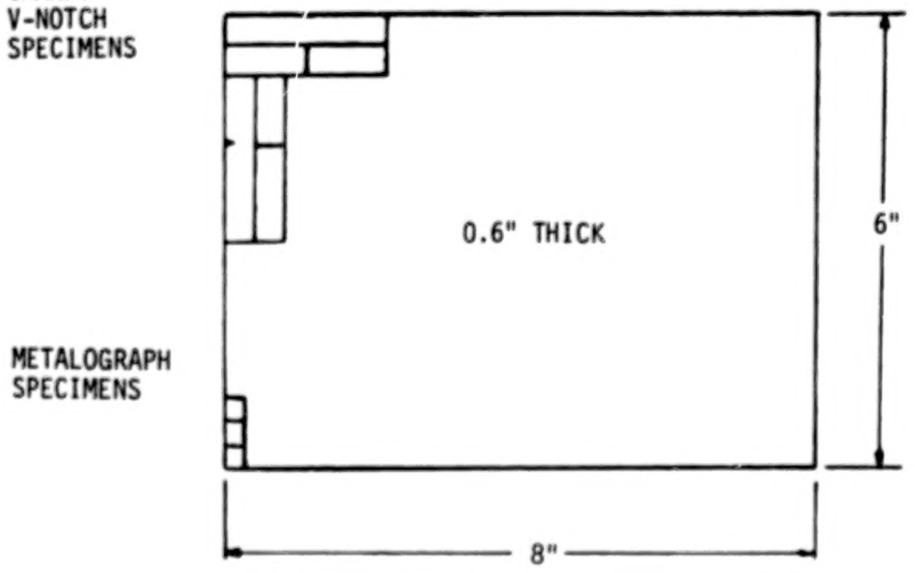
- METALLURGICAL TRANSFORMATION
  - ○ AUSTENITIC TO MARTENSITIC (15-5 PH, 17-4 PH)
- REDISTRIBUTION OF FABRICATION STRESSES
  - ○ INFLUENCED BY GRAIN SIZE

STRESS EFFECTS ON MARTENSITIC PHASE TRANSFORMATION IN AN ANSI 304L STAINLESS STEEL*

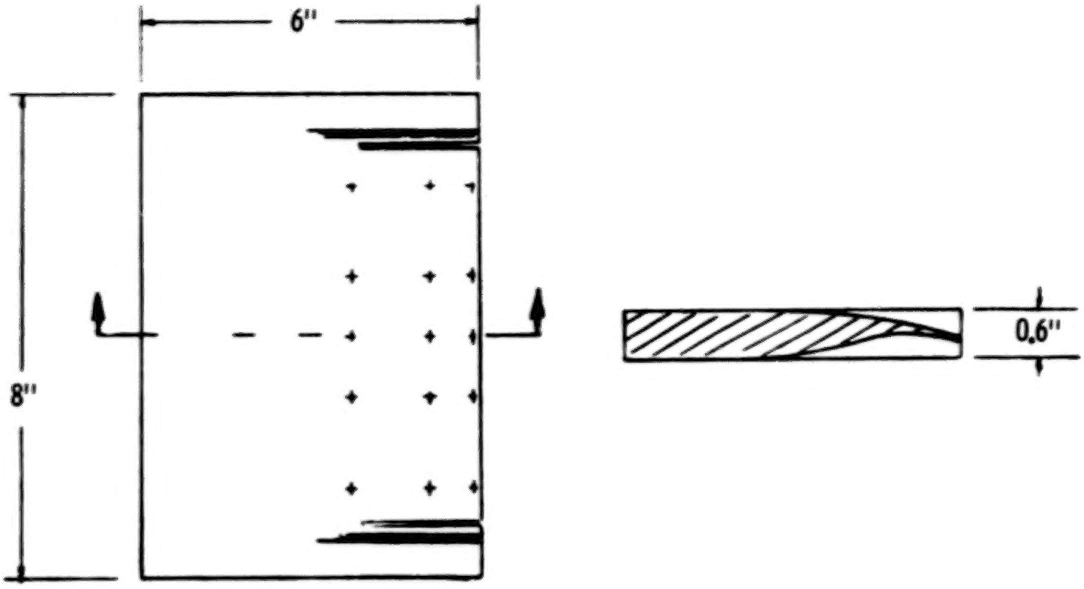


*From R. L. Tober, Materials for Cryogenic Wind Tunnel Testing, National Bureau of Standards, NBSIR 79-1624, 1980, p. 27.

BASIC DIMENSIONAL STABILITY SPECIMEN

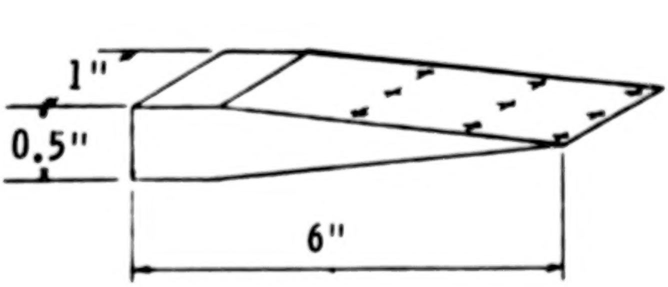

CHARPY
V-NOTCH
SPECIMENS
0.6" THICK
6"
METALOGRAPH
SPECIMENS
8"

SIMULATED AIRFOIL
DIMENSIONAL STABILITY SPECIMEN



DIMENSIONAL STABILITY WEDGE

COMPARISON OF CONVENTIONAL MACHINING
(WORK INDUCED STRESSES)
vs WIRE ELECTRO-DISCHARGE MACHINING
(HEAT AFFECTED ZONE)



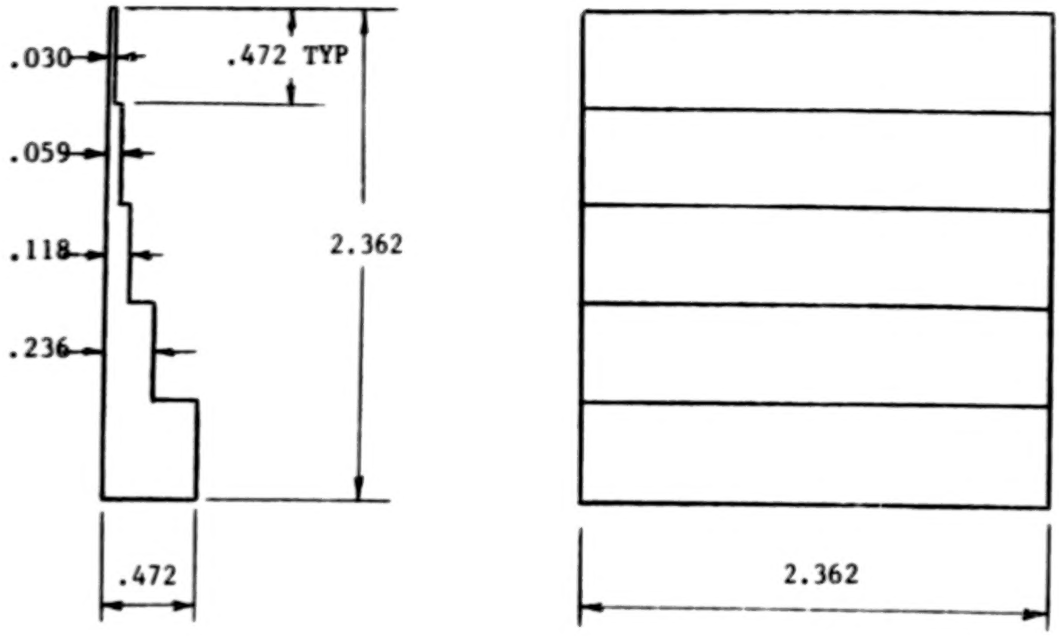
WARPING OF 2-D AIRFOILS OF VARIOUS MATERIALS AND DESIGNS

Airfoil, material, design	Deviation after three cryogenic cycles	
	Upper surface	Lower surface
1027 airfoil, 347 stainless steel, brazed coverplate	high +0.0008 low -0.0016 total 0.0024	high +0.0011 low -0.0007 total 0.0018
0014 airfoil, 15-5 stainless steel, bonded coverplate	high +0.0061 low -0.0019 total 0.0080	high +0.0020 low -0.0071 total 0.0091
65-213 airfoil, 13-8 stainless steel, tongue and groove	high +0.0011 low -0.0005 total 0.0016	high +0.0009 low -0.0001 total 0.0010
5/8-in. by 5-in. by 8-in. sample, NITRONIC 40 stainless steel, tongue and groove	high +0.0005 low -0.0003 total 0.0008	high +0.0000 low -0.0005 total 0.0005

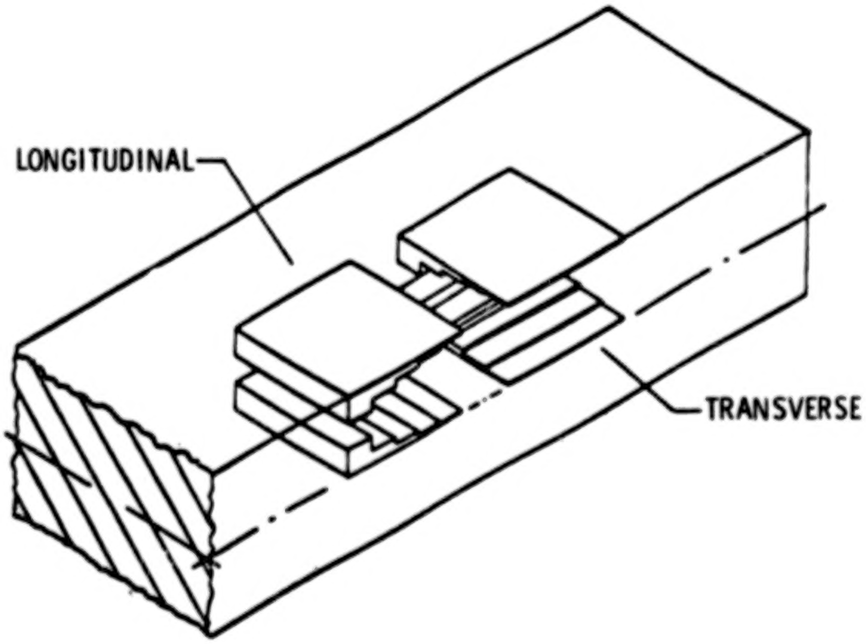
DISTORTION AFTER CRYO CYCLING

		DEVIATION FROM ABSOLUTE FLAT	
		BEFORE	AFTER
NITRONIC 40 (TONGUE IN GROOVE) SIMULATED AIRFOIL	0019		
15-5 PH (H 1025) (E.B.W. COVER PLATE) 6% SUPERCRITICAL AIRFOIL	.0023		
*NITRONIC 40 FLAT SPECIMEN (BONDED COVER PLATE)	.0012	.0013	.0004
VASCOMAX 200 A	.0002	.0003	.0004
VASCOMAX 200 B	.0005	.0013	.0011
VASCOMAX 200 A (SIMULATED AIRFOIL)	.0010		
CUSTOM 450 (1 x 6)	.0009		
*ERROR IN MEASUREMENT SPECIMEN REPROCESSED	.0007		
12 Ni SPECIMENS (.23 x 3 x 3)	.001		

STEPPED DIMENSIONAL STABILITY SPECIMEN


.030
.472 TYP
.059
.118
2.362
.236
.472
2.362

SPECIMEN ORIENTATION


LONGITUDINAL
TRANSVERSE

MATERIALS INVESTIGATED

NITRONIC 40
15-5 PH
VASCOMAX 200 CVN
PH 13-8 Mo
347 STAINLESS STEEL
CUSTOM 450
2024 ALUMINUM
12 Ni STEELS

FURTHER INVESTIGATIONS

VASCOMAX 200 CVN
PH 13-8 Mo
A-286
9 Ni STEEL
HP 9-4-20
NITRONIC 40
12 Ni STEELS
AF 1410
300 SERIES STAINLESS STEEL
5000 & 6000 SERIES ALUMINUM
COPPER ALLOYS
NICKEL ALLOYS

FABRICATION TECHNIQUES

A. FORGING
B. CASTING
C. POWDER METALLURGY
D. DIFFUSION BRAZING
E. DIFFUSION BONDING
F. SUPER PLASTIC FORMING
G. ELECTRO-DEPOSITING (PLATING)
H. EDM-GRINDING & CHEM-GRINDING
I. ELECTRO POLISHING

CONCLUSIONS

STABILITY

- O VASCOMAX 200 CVN
- O PH 13-8 Mo & A-286
- O AUSTENITIC STEELS (300 SERIES, NITRONIC 40)
- O DUAL PHASE ALLOYS (15-5 PH, AF 1410)

CONCERNS & PROSPECTS

- O CORROSION
- O SENSITIVITY OF ALLOYS TO MANUFACTURING, FABRICATION & HEAT TREATMENT PROCEDURES
- O 12 Ni STEELS & GRAIN REFINEMENT

METALLURGICAL STUDIES OF NITRONIC 40 WITH REFERENCE TO ITS USE FOR CRYOGENIC WIND TUNNEL MODELS

David Wigley
University of Southampton
Southampton, England

A comprehensive study was carried out to investigate the characteristics of NITRONIC 40 in connection with its use in cryogenic wind tunnel models (ref. 1). In particular, the effects of carbide and sigma-phase precipitation resulting from heat treatment and the presence of delta ferrite were evaluated in relation to their effects on mechanical properties and the potential consequences of such degradation. (See figs. 1 through 20.)

Methods were examined for desensitizing the material and for possible removal of delta ferrite as a means of restoring the material to its advertised properties. It was found that heat treatment followed by cryogenic quenching is a technique capable of desensitizing NITRONIC 40. However, it was concluded that it is extremely difficult, if not impossible, to remove the delta ferrite from the existing stock of material. Furthermore, heat treatments for removing delta ferrite have to take place at temperatures that cause very large grain growth. The implications of using the degraded NITRONIC 40 material for cryogenic model testing were reviewed, and recommendations were submitted with regard to the acceptability of the material.

The experience gained from the study of NITRONIC 40 clearly identifies the need to implement a policy for purchasing top-quality materials for cryogenic wind tunnel model applications. The study also exemplifies the need for careful evaluation and analysis of processes used in the fabrication of metallic alloys for cryogenic use.

REFERENCE

1. Wigley, D. A.: The Metallurgical Structure and Mechanical Properties at Low Temperature of NITRONIC 40, With Particular Reference to Its Use in the Construction of Models for Cryogenic Wind Tunnels. NASA CR-165907, 1982.

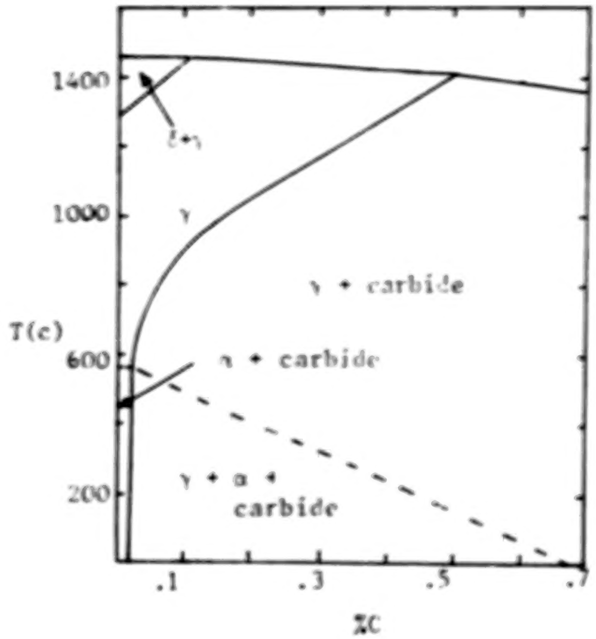


Figure 1.- Phase diagram for 18Cr-8Ni stainless steel. (From ref. 1.)

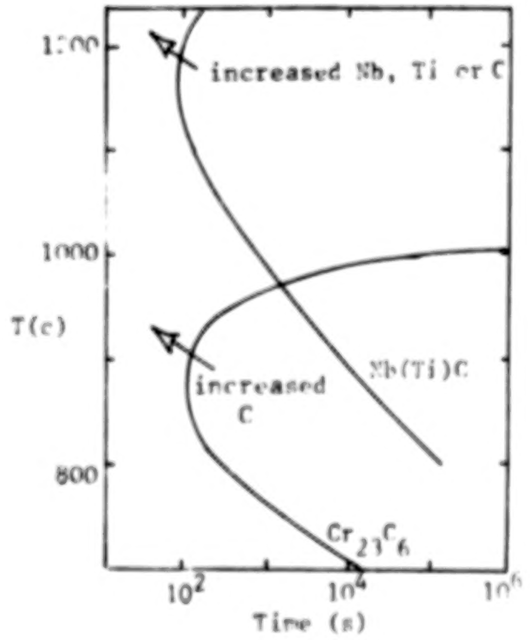


Figure 2.- T.T.T. (time-temperature transformation) curves for growth of $M_{23}C_6$ and Nb(Ti)C in Cr-Ni stainless steel. (From ref. 1.)

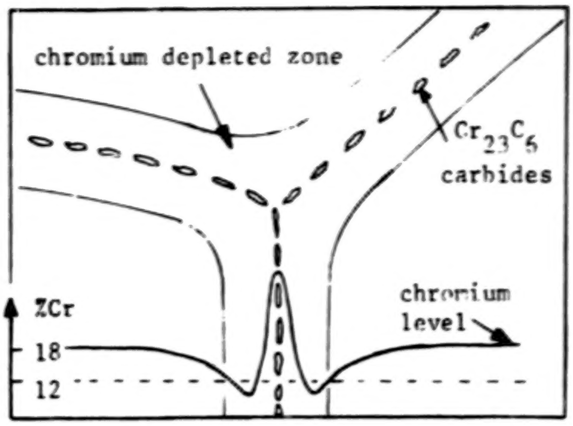

chromium depleted zone
$Cr_{23}C_6$ carbides
%Cr
chromium level
18
12

Figure 3.- Schematic representation of carbide precipitation and chromium depletion in 18/8 stainless steel. (From ref. 1.)

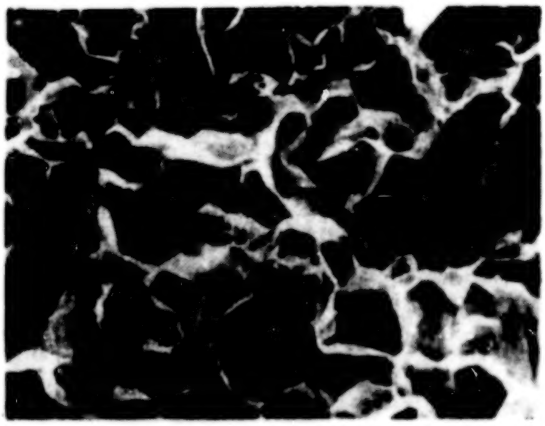
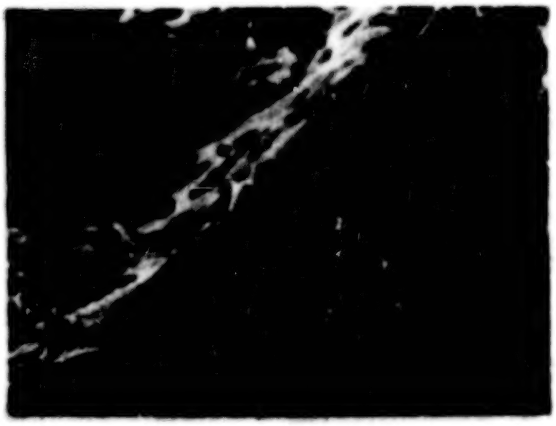


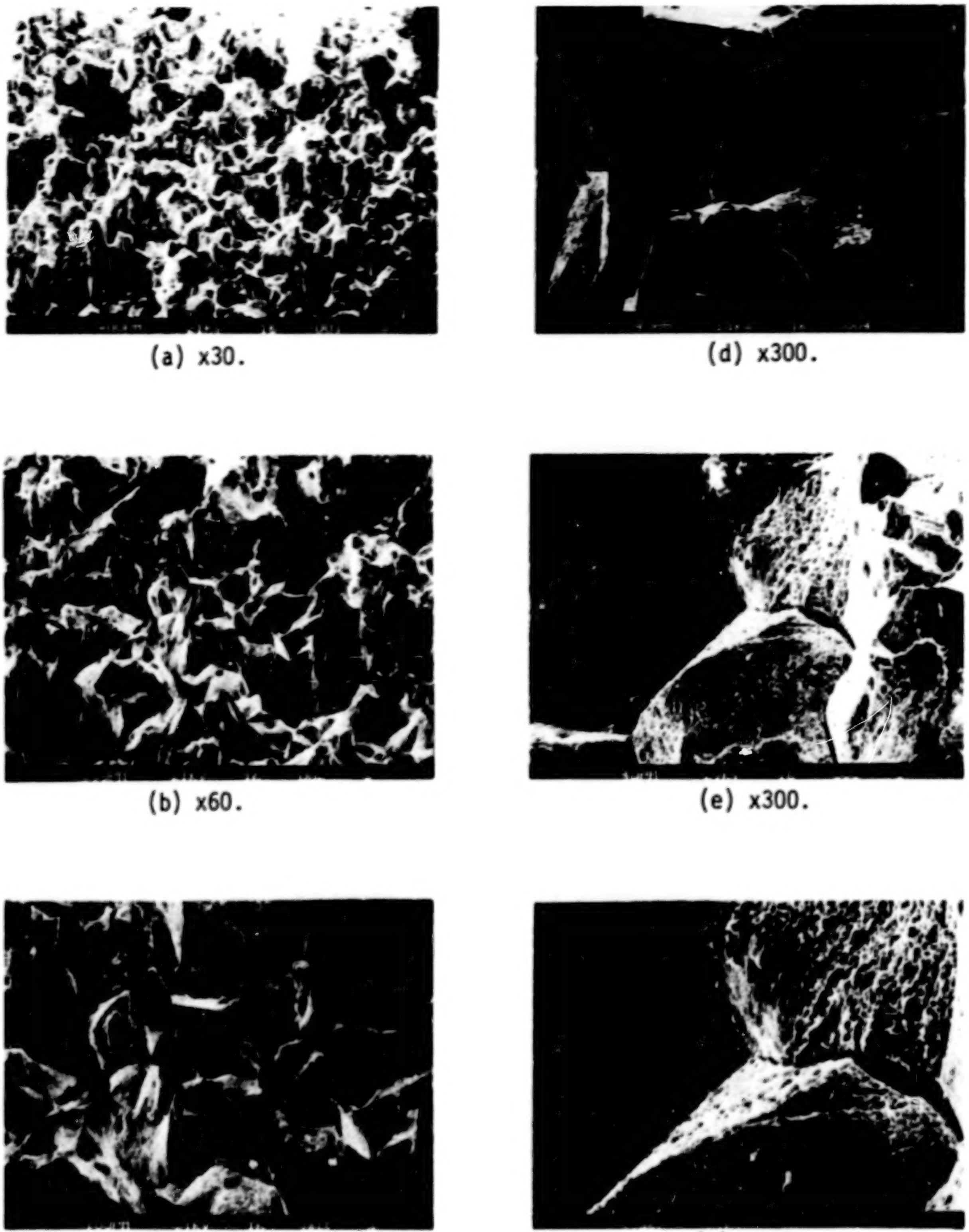
Figure 4.- Stereoscan view at x400 of intergranular fracture in 18/8 stainless steel. (From ref. 1.)

(a) Stereoscan, x400.



(b) Stereoscan, x1.6K.

Figure 5.- Multiple nucleation of ductile dimples at grain boundary carbides during intergranular fracture of NITRONIC 40. (From ref. 1.)



(a) x30.

(d) x300.

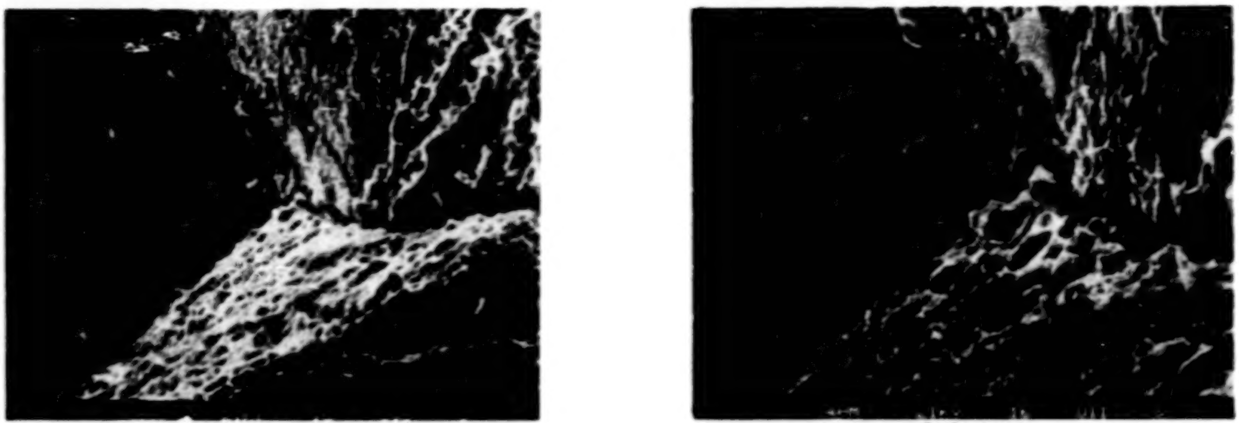
(b) x60.

(e) x300.

(c) x120.

(f) x600.

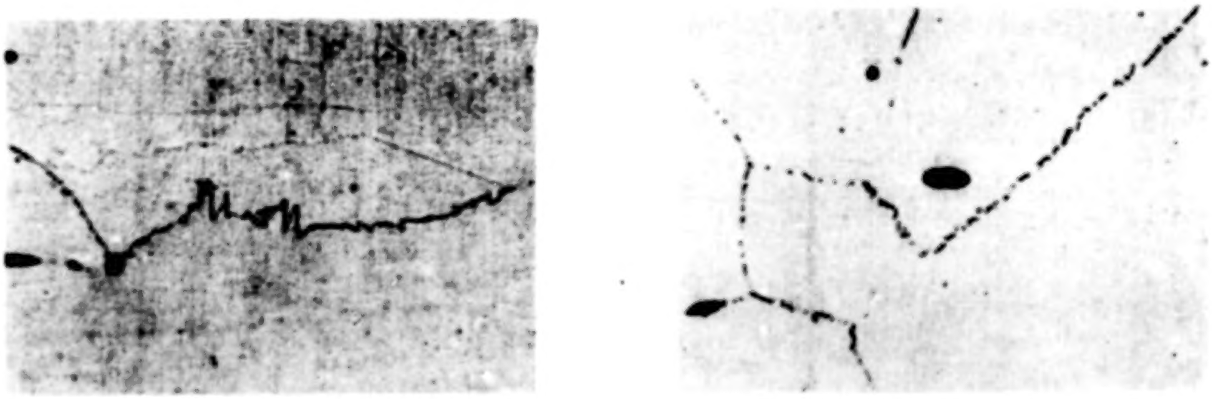
Figure 6.- Stereoscan views of -320°F Charpy fracture surface of highly sensitized NITRONIC 40. Specimen ST168. (From ref. 1.)



(g) x1.2K.

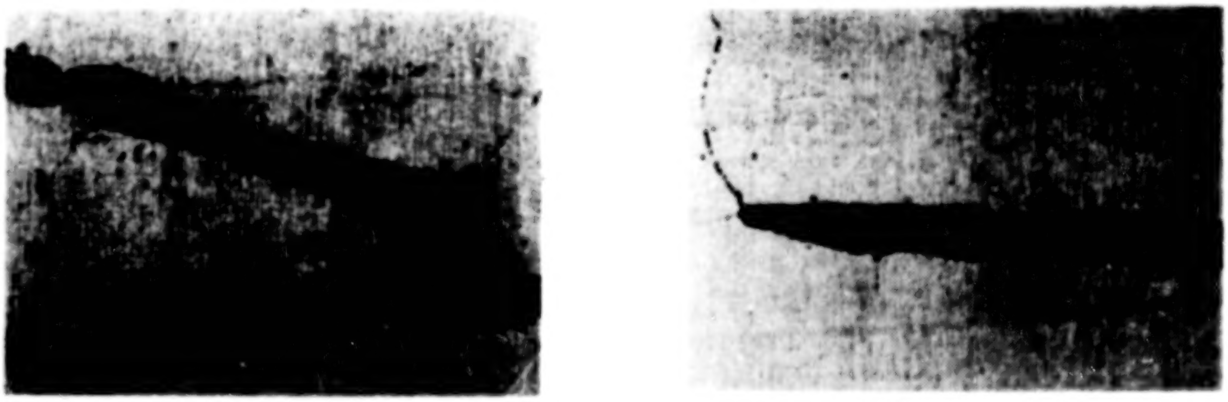
(h) x3K.

Figure 6.- Concluded.



(a) ST5, x600.

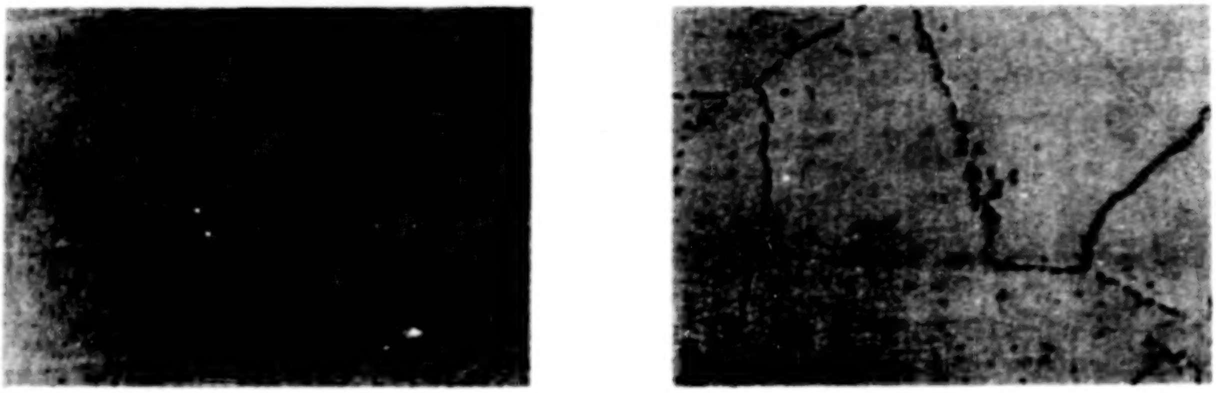
(c) ST24, x600.



(b) ST5, x600.

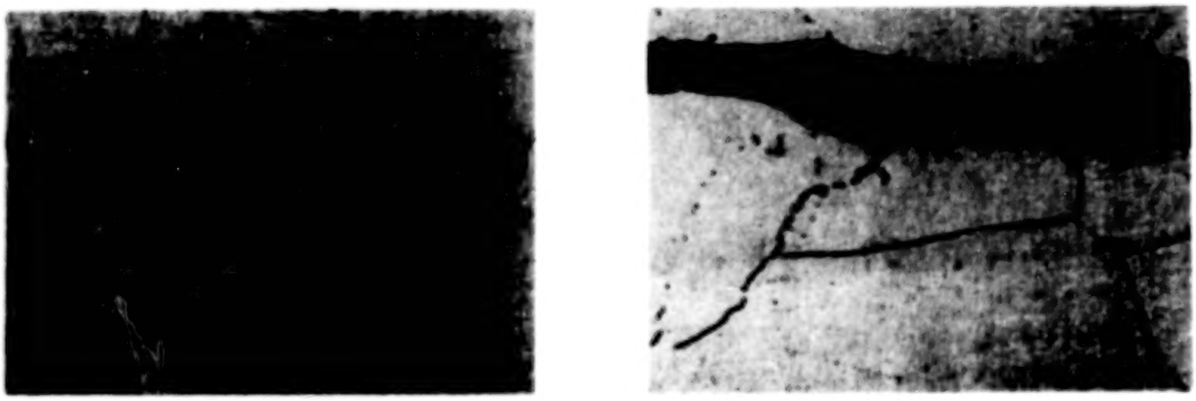
(d) ST24, x600.

Figure 7.- Development of sigma-phase precipitates at grain boundaries and within delta ferrite during heat treatment at 1380°F (750°C) in sample S. (From ref. 1.)



(e) ST72, x600.

(g) ST168, x600.



(f) ST72, x600.

(h) ST168, x600.

Figure 7.- Concluded.

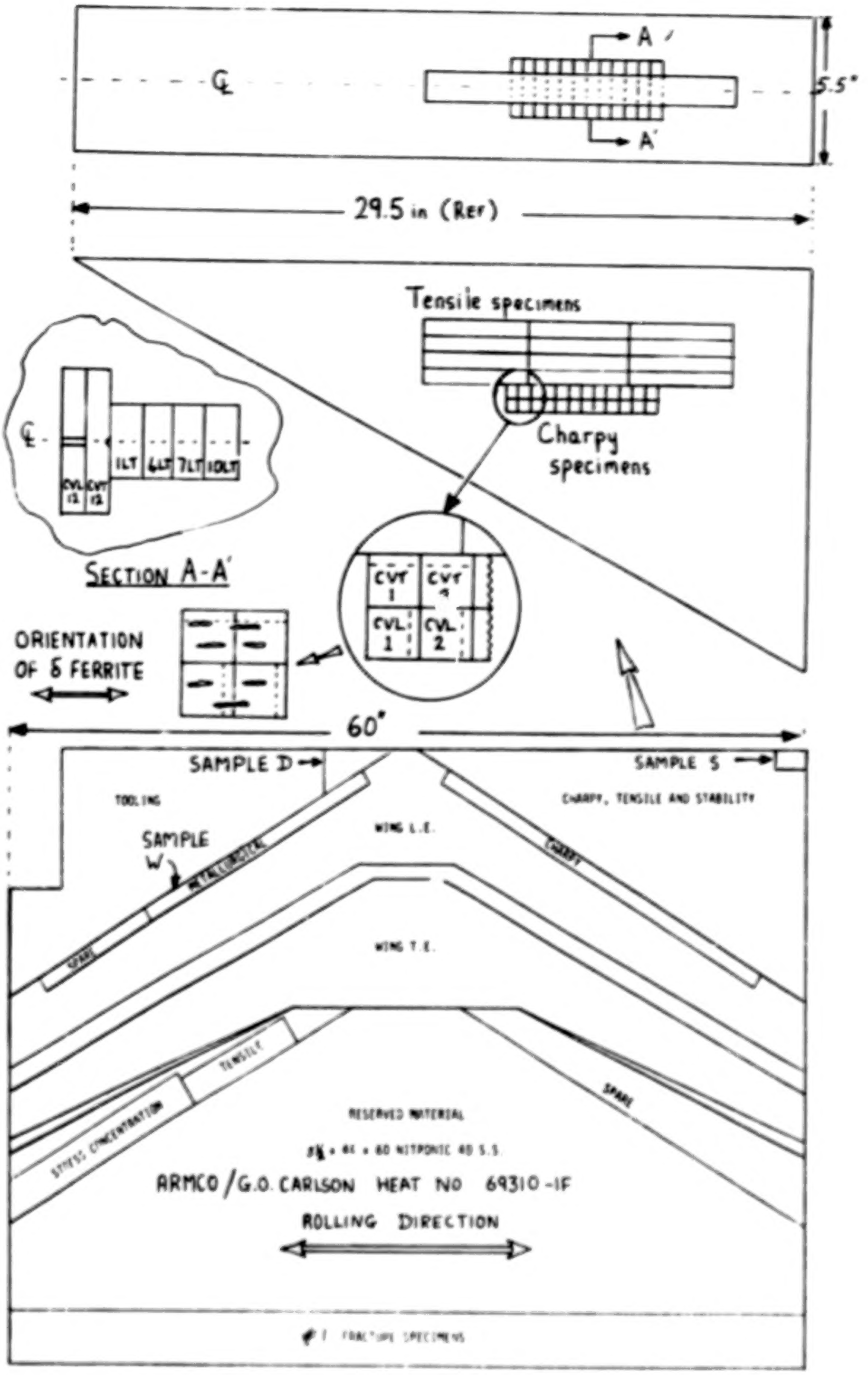

A
A'
℄
5.5"
29.5 in (Ref)
Tensile specimens
Charpy specimens
℄
CVL 12
CVT 12
1LT
6LT
7LT
10LT
SECTION A-A'
CVT 1
CVT 2
CVL 1
CVL 2
ORIENTATION OF δ FERRITE
60"
SAMPLE D
SAMPLE S
TOOLING
CHARPY, TENSILE AND STABILITY
SAMPLE W
METALLOGRAPHICAL
WING L.E.
CHARPY
SPARE
WING T.E.
TENSILE
STRESS CONCENTRATION
SPARE
RESERVED MATERIAL
46 × 60 NITRONIC 40 S.S.
ARMCO / G.O. CARLSON HEAT NO 69310-1F
ROLLING DIRECTION
#1 FRACTURE SPECIMENS

Figure 8.- Location of Charpies, tensiles, and samples D, S, and W. (From ref. 1.)

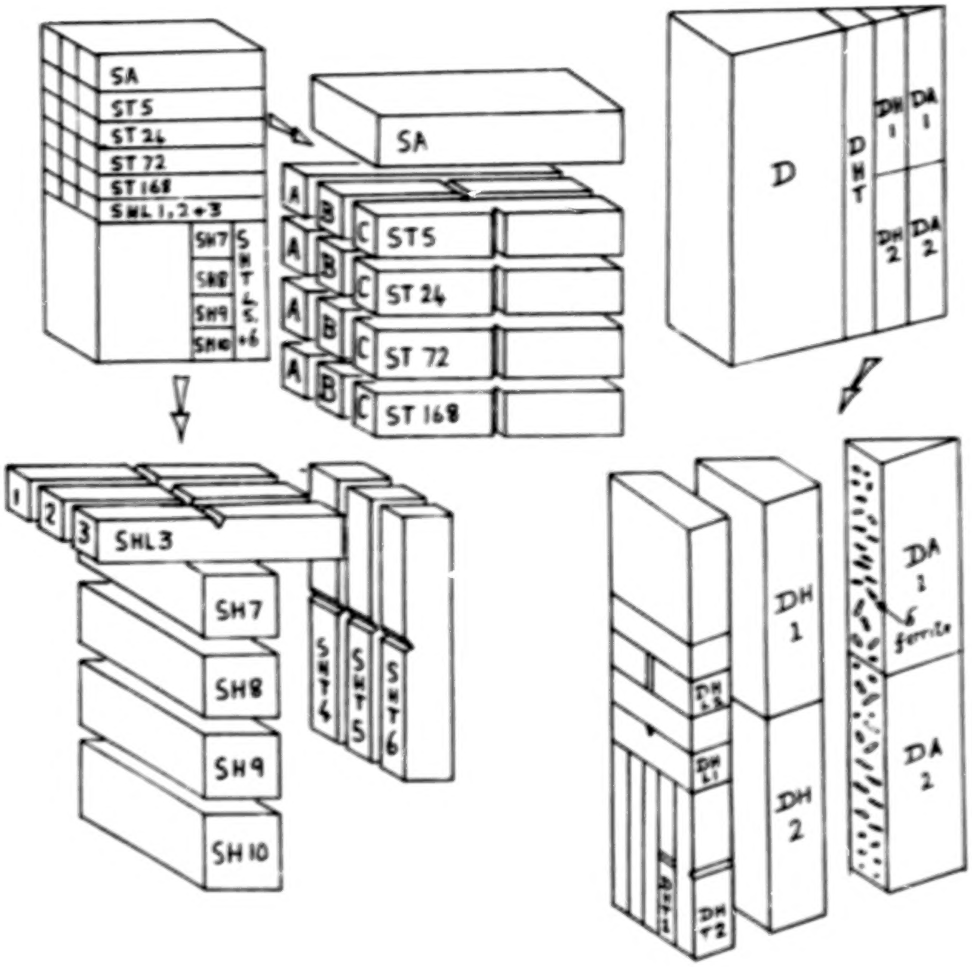

SA
ST5
ST24
ST72
ST168
SHL1,2+3
SH7
SH8
SH9
SH10
SHT 4, 5, +6
A
B
C
ST5
ST24
ST72
ST168
D
DHT
DH 1
DA 1
DH 2
DA 2
1
2
3
SHL3
SH7
SH8
SH9
SH10
SHT 4
SHT 5
SHT 6
DH 1
DH 2
DA 1
DA 2
ferrite
DH T2

Figure 9.- Location of specimens in samples S and D from 5.5-in. plate. (From ref. 1.)

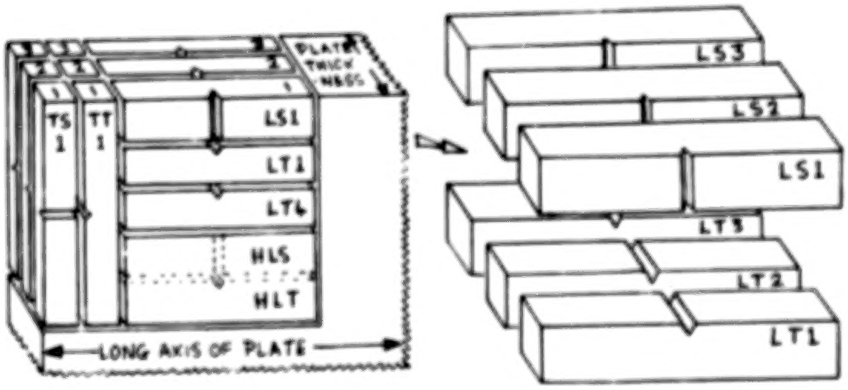


PLATE THICKNESS
TS 1
TT 1
LS1
LT1
LT6
HLS
HLT
LONG AXIS OF PLATE
LS3
LS2
LS1
LT3
LT2
LT1

Figure 10.- Location of specimens in samples M and L from 1.25-in. plate. (From ref. 1.)

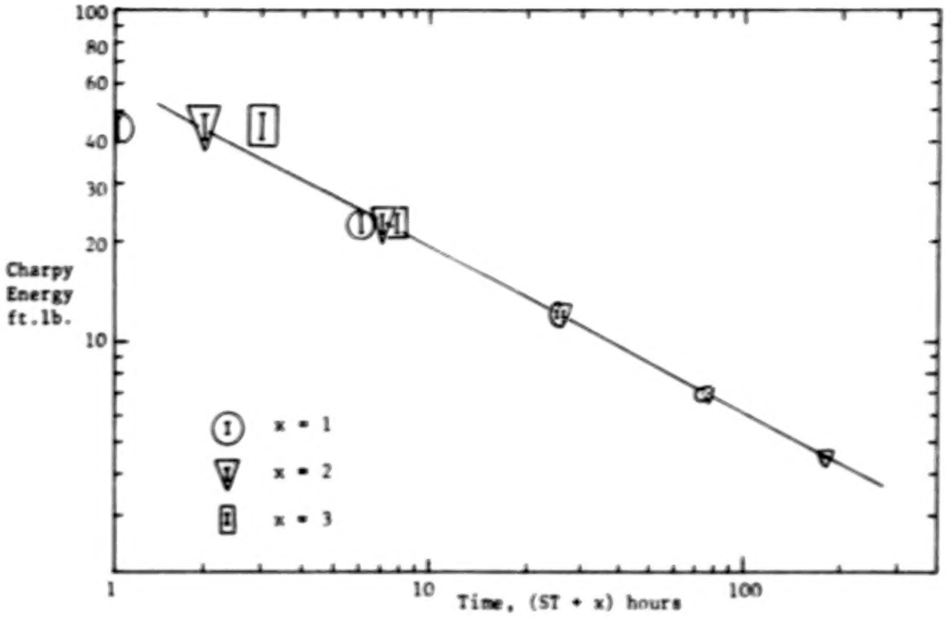


Figure 11.- Relationship between Charpy energy and sensitizing time in NITRONIC 40. (From ref. 1.)

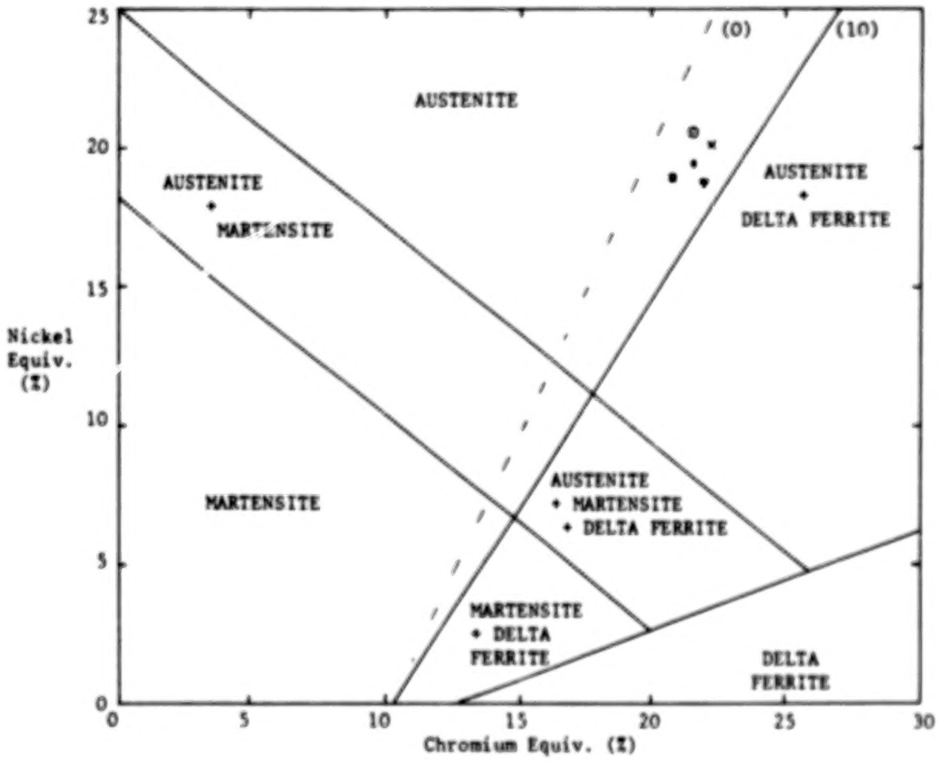
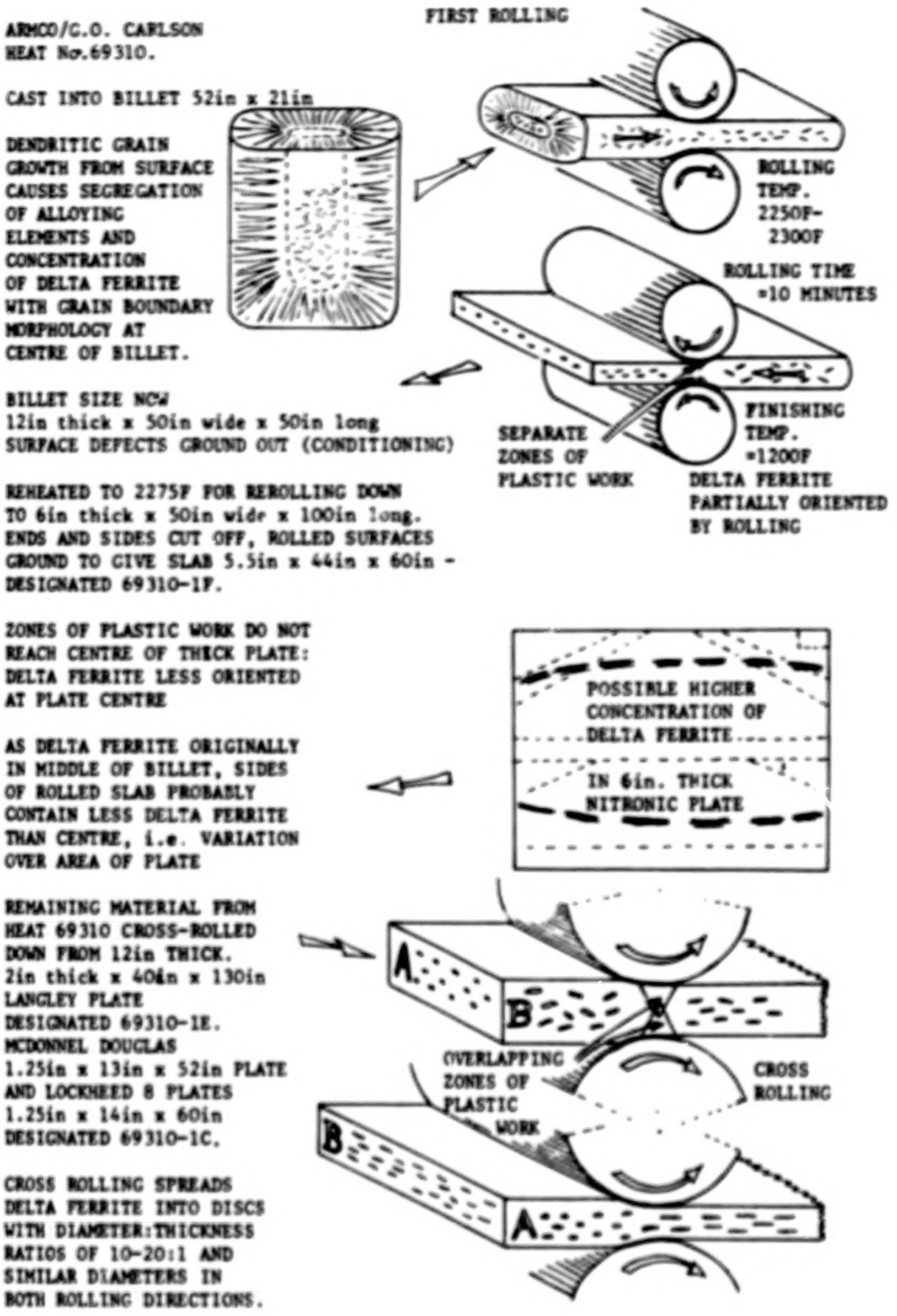


Figure 12.- Schaeffler diagram showing location of NITRONIC 40 samples. (From ref. 1.)



ARMCO/G.O. CARLSON
HEAT No.69310.

CAST INTO BILLET 52in x 21in

DENDRITIC GRAIN GROWTH FROM SURFACE CAUSES SEGREGATION OF ALLOYING ELEMENTS AND CONCENTRATION OF DELTA FERRITE WITH GRAIN BOUNDARY MORPHOLOGY AT CENTRE OF BILLET.

BILLET SIZE NOW
12in thick x 50in wide x 50in long
SURFACE DEFECTS GROUND OUT (CONDITIONING)

REHEATED TO 2275F FOR REROLLING DOWN TO 6in thick x 50in wide x 100in long. ENDS AND SIDES CUT OFF, ROLLED SURFACES GROUND TO GIVE SLAB 5.5in x 44in x 60in - DESIGNATED 69310-1F.

ZONES OF PLASTIC WORK DO NOT REACH CENTRE OF THICK PLATE: DELTA FERRITE LESS ORIENTED AT PLATE CENTRE

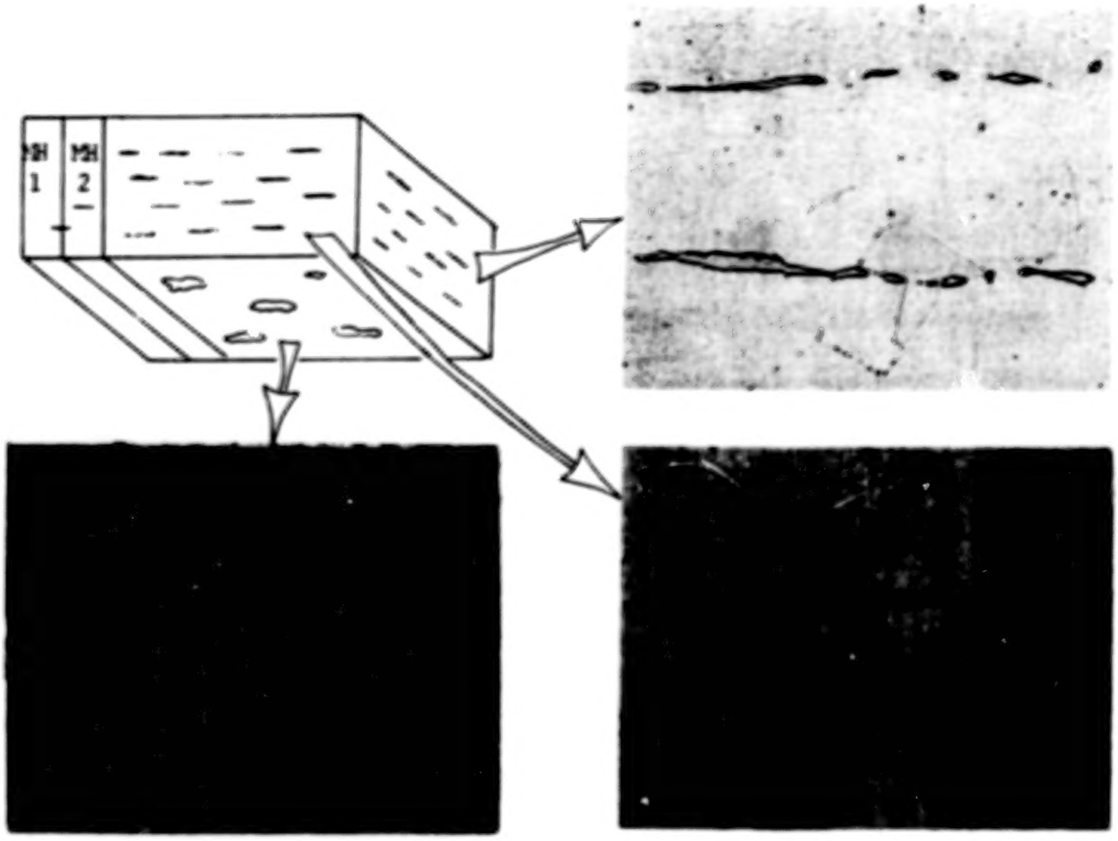
AS DELTA FERRITE ORIGINALLY IN MIDDLE OF BILLET, SIDES OF ROLLED SLAB PROBABLY CONTAIN LESS DELTA FERRITE THAN CENTRE, i.e. VARIATION OVER AREA OF PLATE

REMAINING MATERIAL FROM HEAT 69310 CROSS-ROLLED DOWN FROM 12in THICK.
2in thick x 40in x 130in LANGLEY PLATE DESIGNATED 69310-1E.
MCDONNEL DOUGLAS 1.25in x 13in x 52in PLATE AND LOCKHEED 8 PLATES 1.25in x 14in x 60in DESIGNATED 69310-1C.

CROSS ROLLING SPREADS DELTA FERRITE INTO DISCS WITH DIAMETER:THICKNESS RATIOS OF 10-20:1 AND SIMILAR DIAMETERS IN BOTH ROLLING DIRECTIONS.

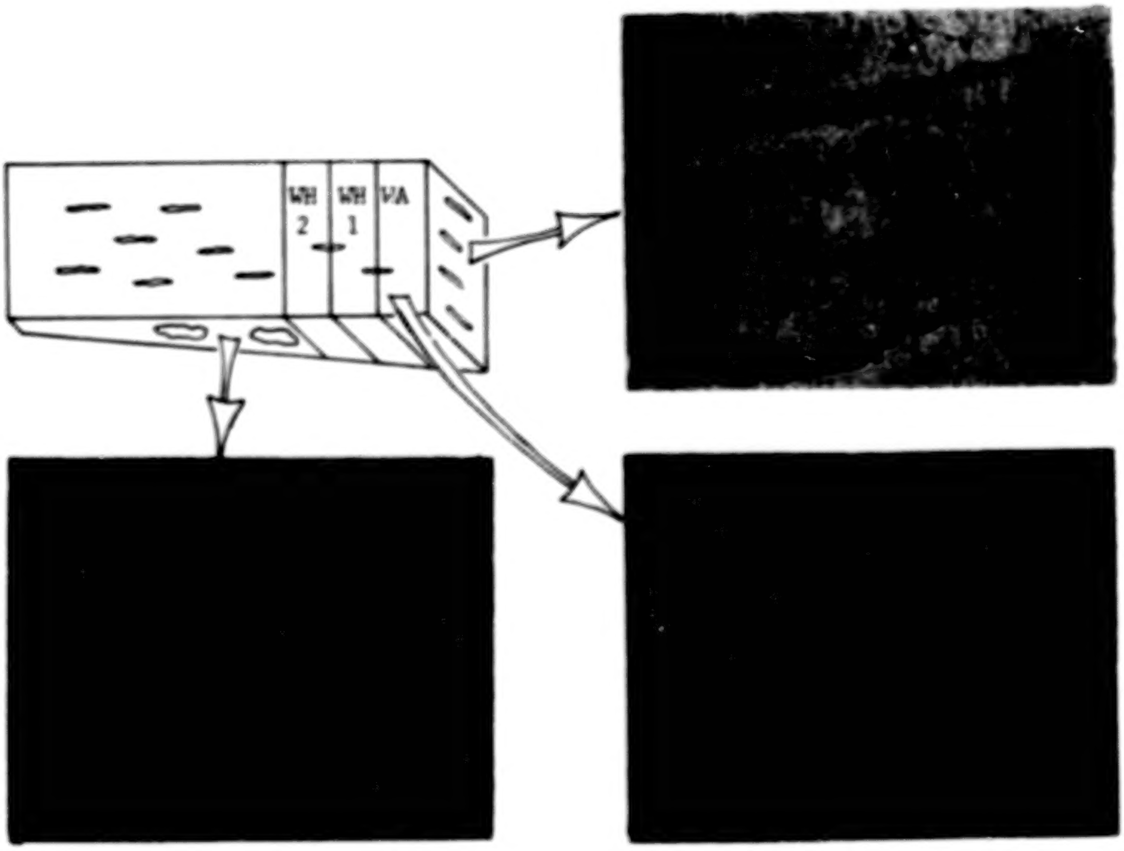
FIRST ROLLING
ROLLING TEMP. 2250F-2300F
ROLLING TIME ≈10 MINUTES
SEPARATE ZONES OF PLASTIC WORK
FINISHING TEMP. ≈1200F
DELTA FERRITE PARTIALLY ORIENTED BY ROLLING
POSSIBLE HIGHER CONCENTRATION OF DELTA FERRITE
IN 6in. THICK NITRONIC PLATE
A
B
OVERLAPPING ZONES OF PLASTIC WORK
CROSS ROLLING
B
A

Figure 13.- Schematic representation of the effect of processing on the morphology of delta ferrite in NITRONIC 40. (From ref. 1.)



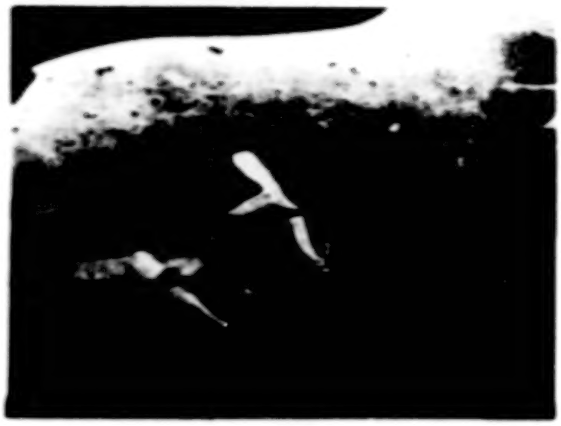
(a) McDonnell Douglas 1.25-in. plate (x300).

Figure 14.- Schematic representation of directionality in microstructure of two samples of rolled NITRONIC 40 plate. (From ref. 1.)

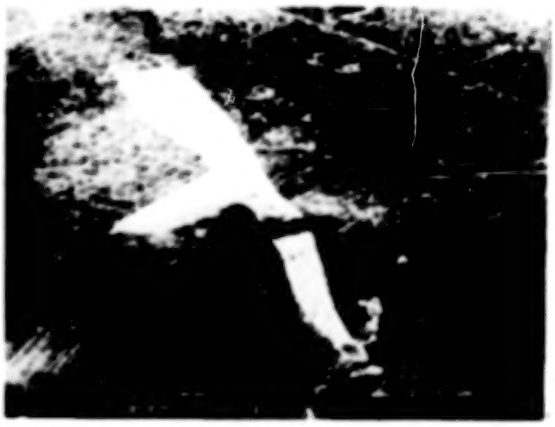


(b) Offcut from Langley 5.5-in. plate for Pathfinder I wing (x300).

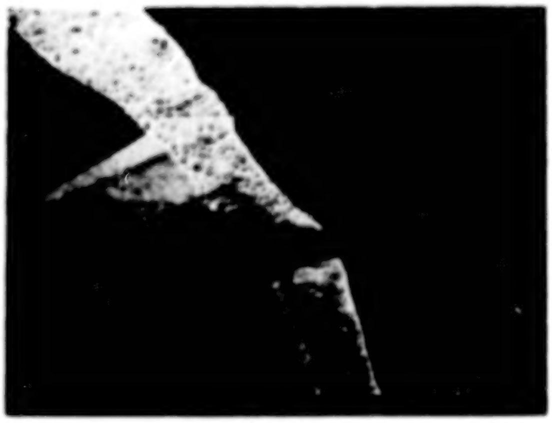
Figure 14.- Concluded.



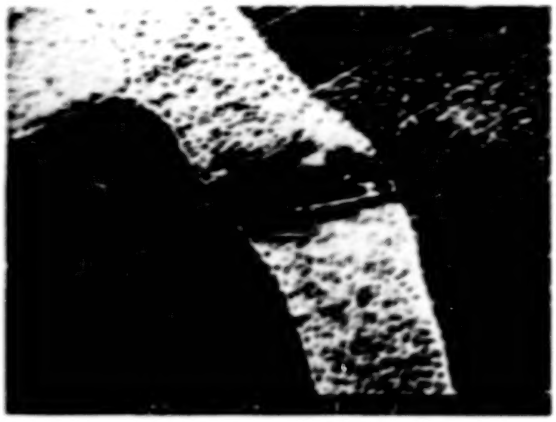
(a) x200.



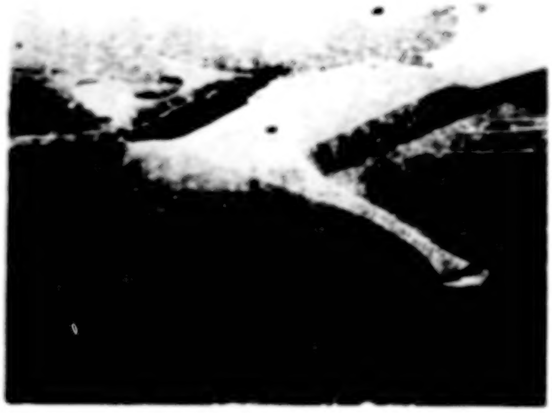
(b) x500.



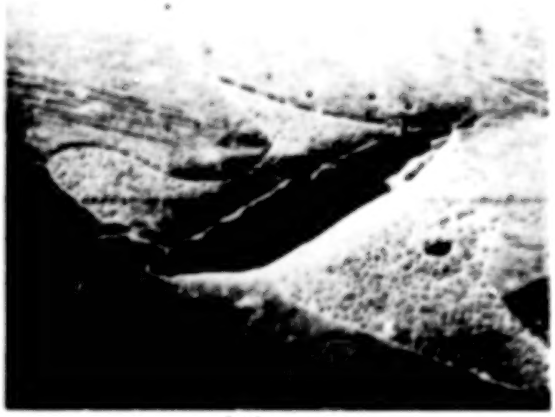
(c) x1K.



(d) x2K.

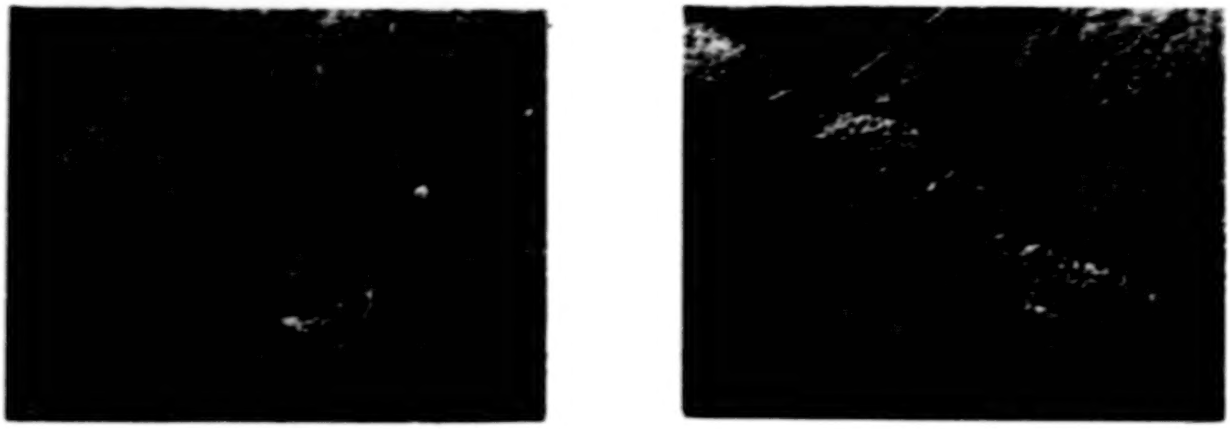


(e) x500.



(f) x1K.

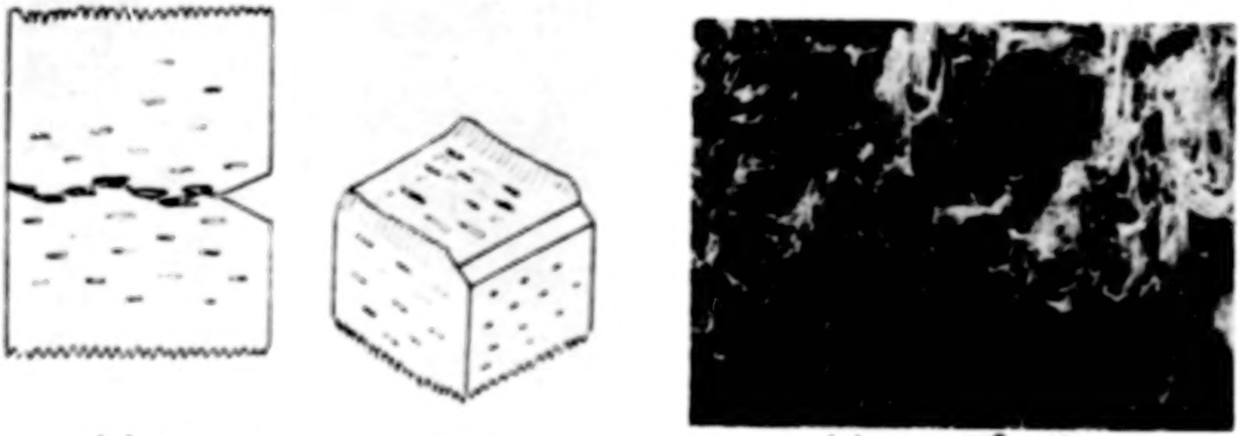
Figure 15.- Stereoscan views of cleavage cracks in delta ferrite on polished and etched surface adjacent to fracture. (From ref. 1.)



(g) x2K.

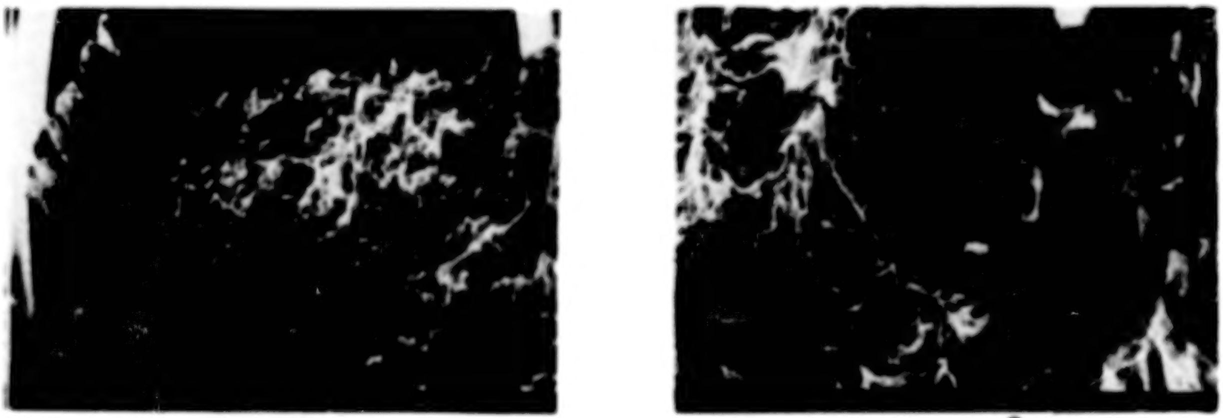
(h) x2K.

Figure 15.- Concluded.



(a) Schematic view of SHT4.

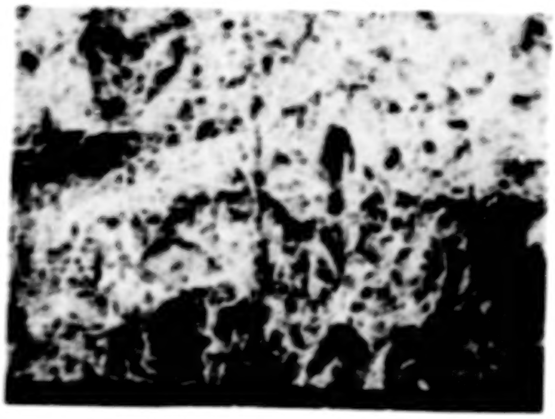
(c) x63, 75° tilt.



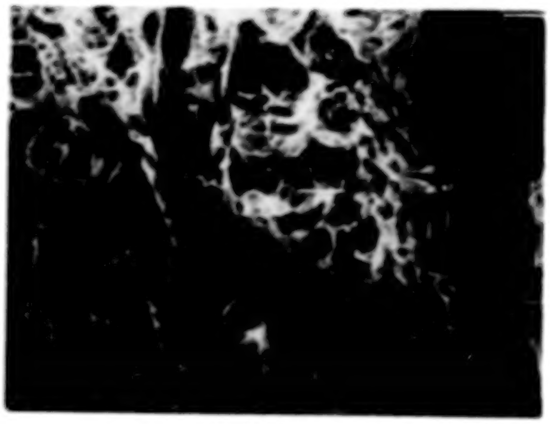
(b) x13, 75° tilt.

(d) x300, 75° tilt.

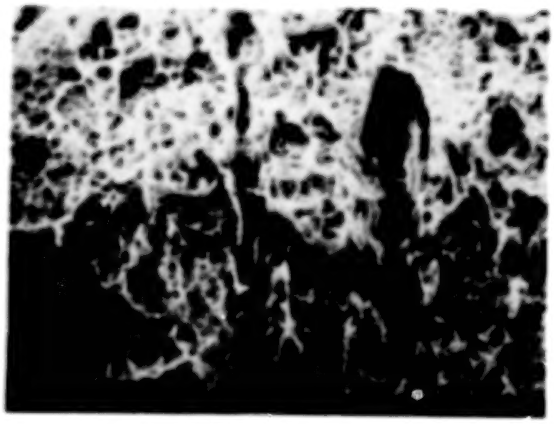
Figure 16.- Stereoscan fiews of 77 K Charpy fracture surface of desensitized NITRONIC 40 with delta ferrite oriented perpendicular to bar. (From ref. 1.)



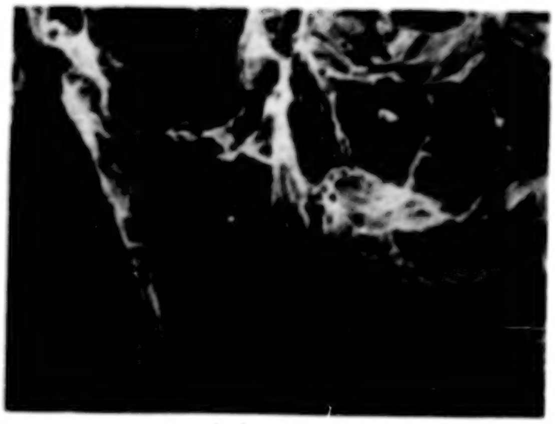
(e) x40, no tilt.



(g) x160.

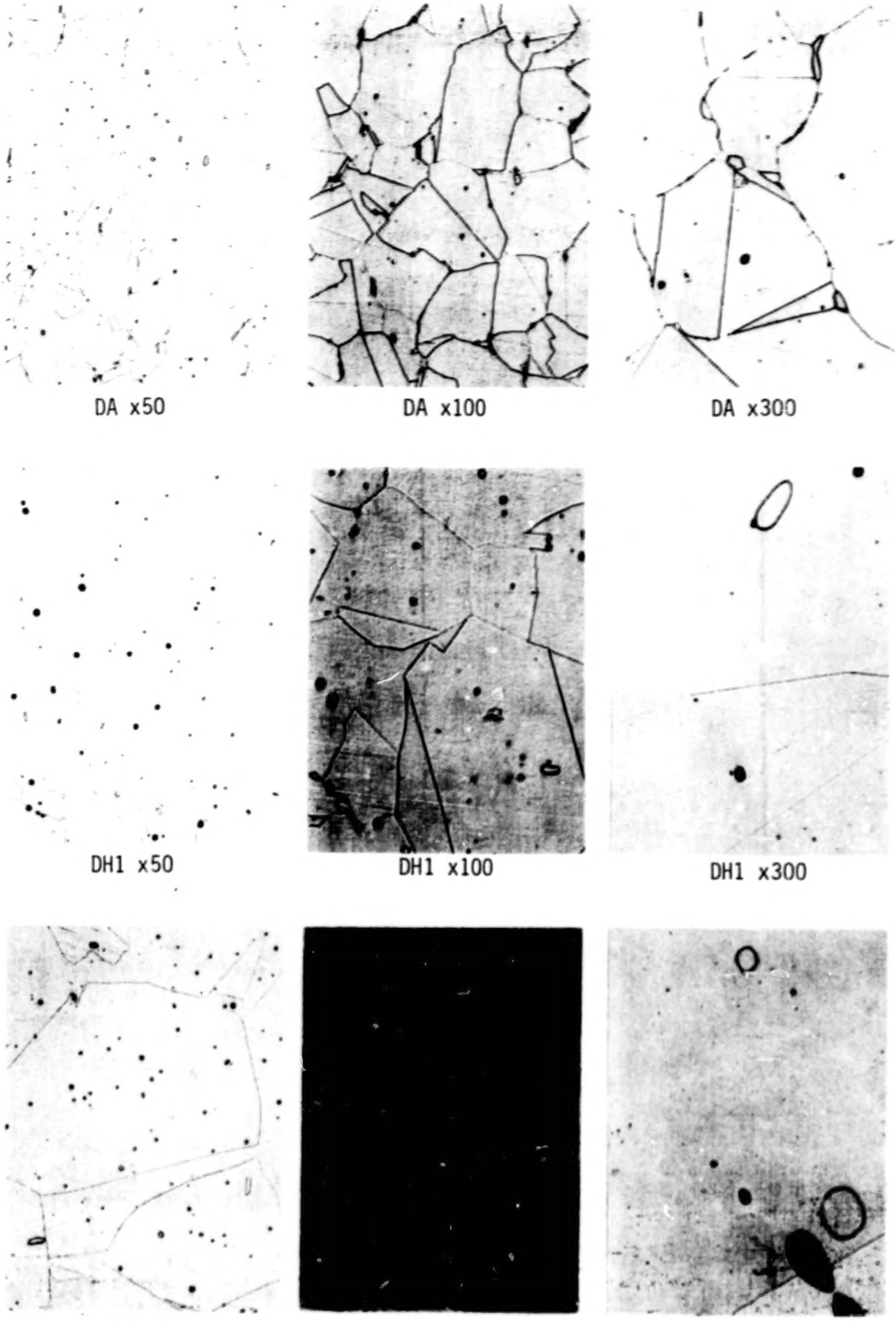


(f) x80.



(h) x400.

Figure 16.- Concluded.

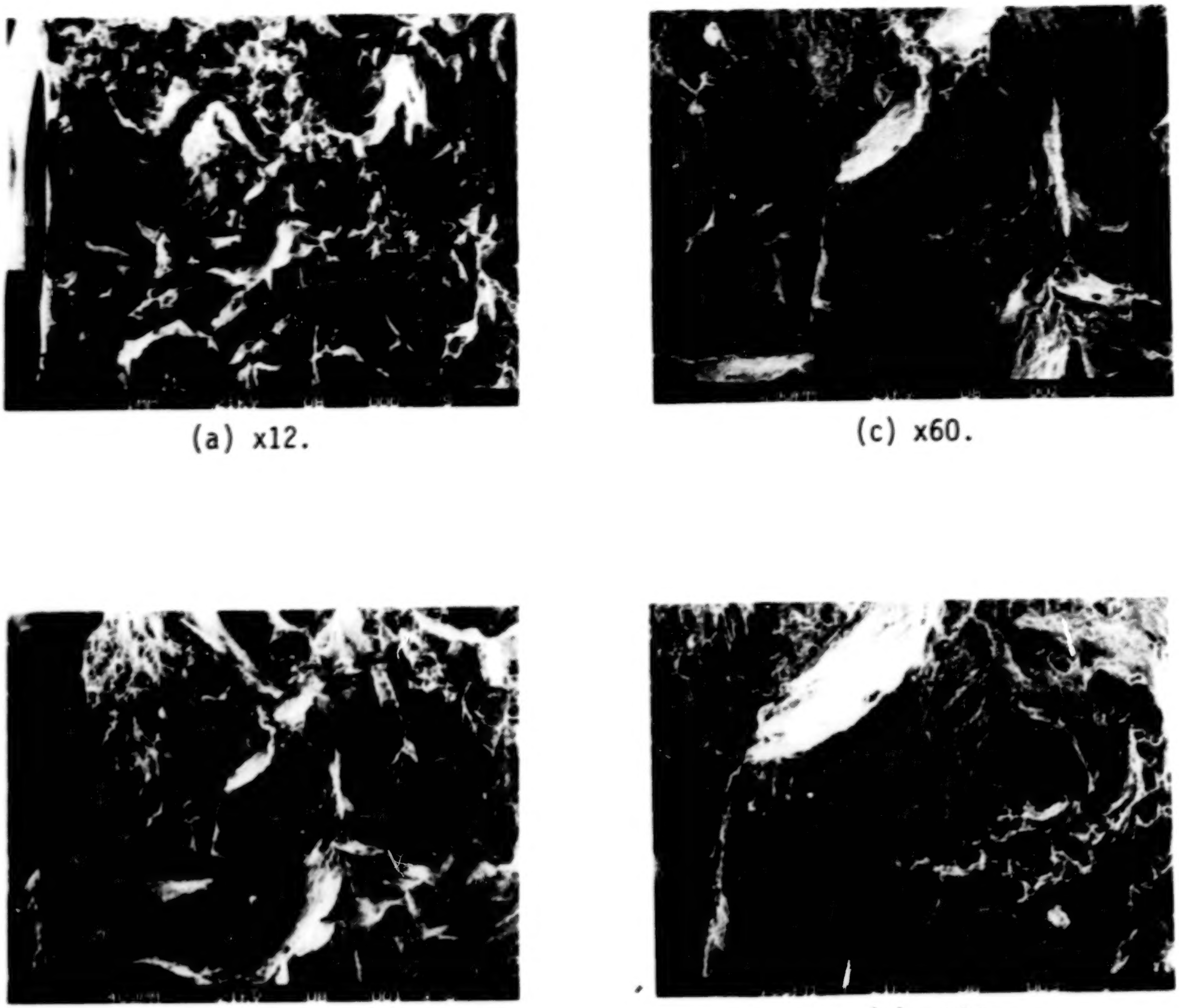


DA x50 DA x100 DA x300

DH1 x50 DH1 x100 DH1 x300

DH2 x50 DH2 x100 DH2 x300

Figure 17.- Sample D. A = as received; H1 = 2200°F, 2 hr; H2 = 2200°F, 8 hr. (From ref. 1.)



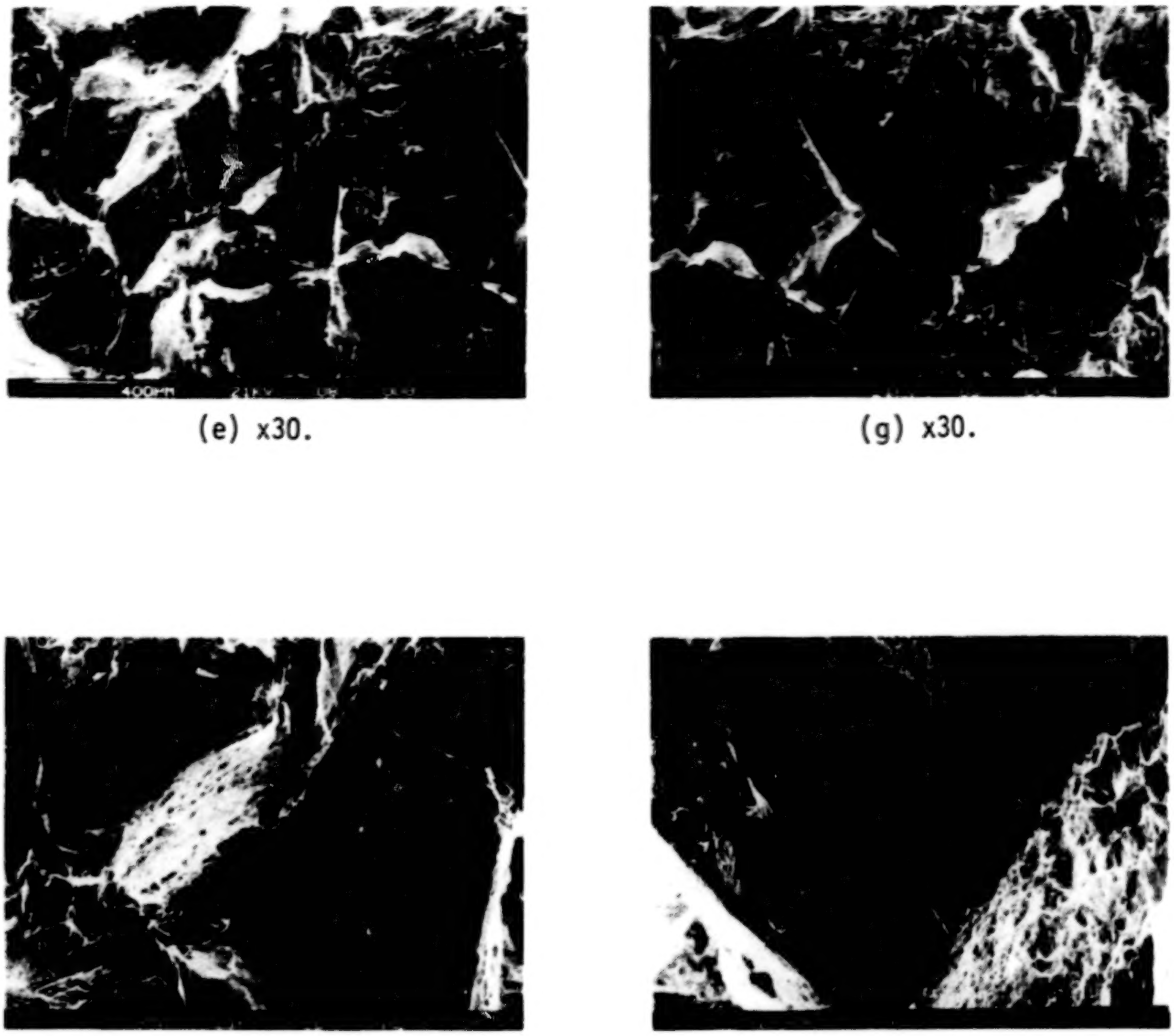
(a) x12.

(c) x60.

(b) x30.

(d) x120.

Figure 18.- Stereoscan views of -320°F Charpy surface on NITRONIC 40 sample DH2 showing very large grains. (From ref. 1.)



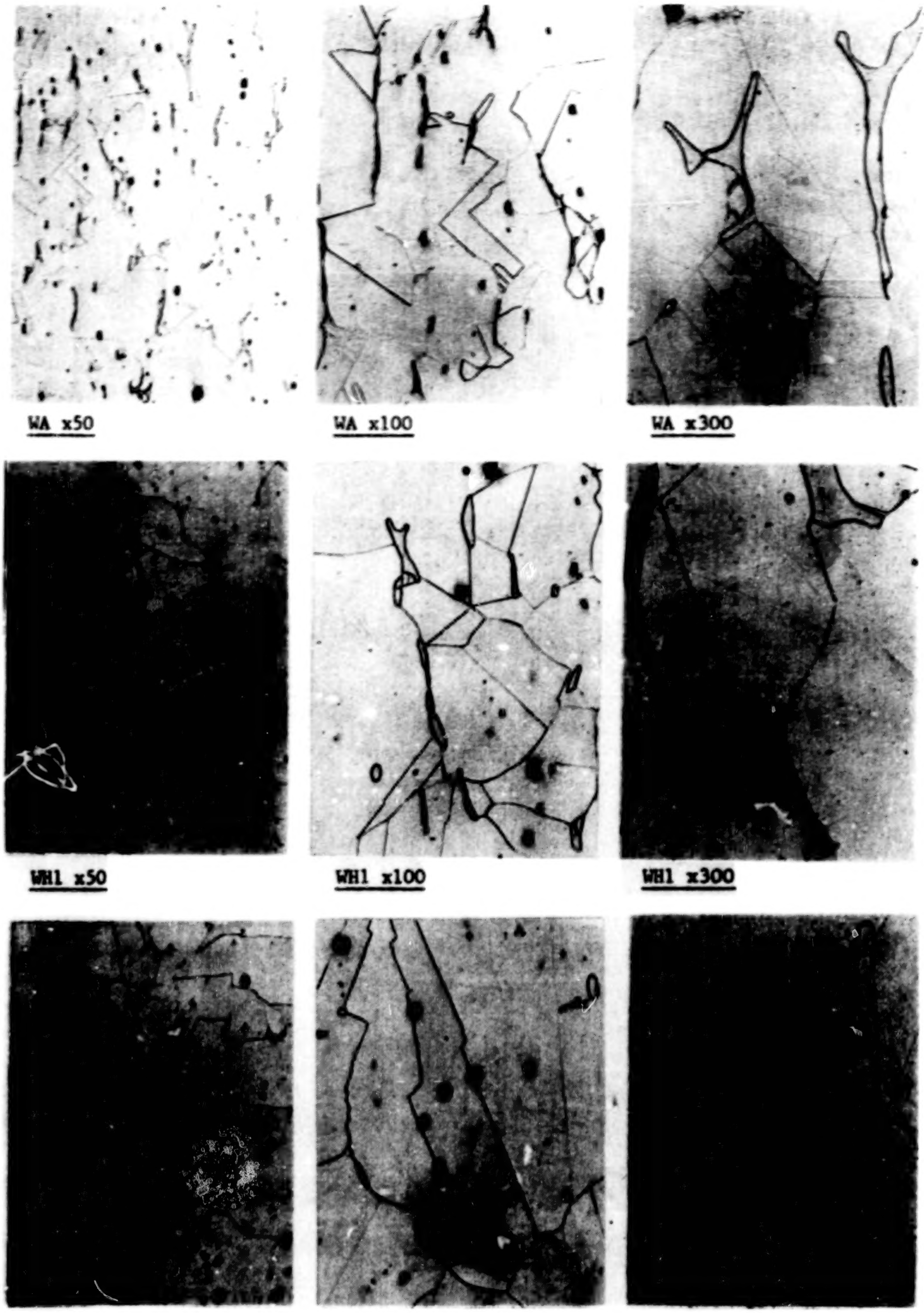
(e) x30.

(g) x30.

(f) x120.

(h) x120.

Figure 18.- Concluded.



WA x50

WA x100

WA x300

WH1 x50

WH1 x100

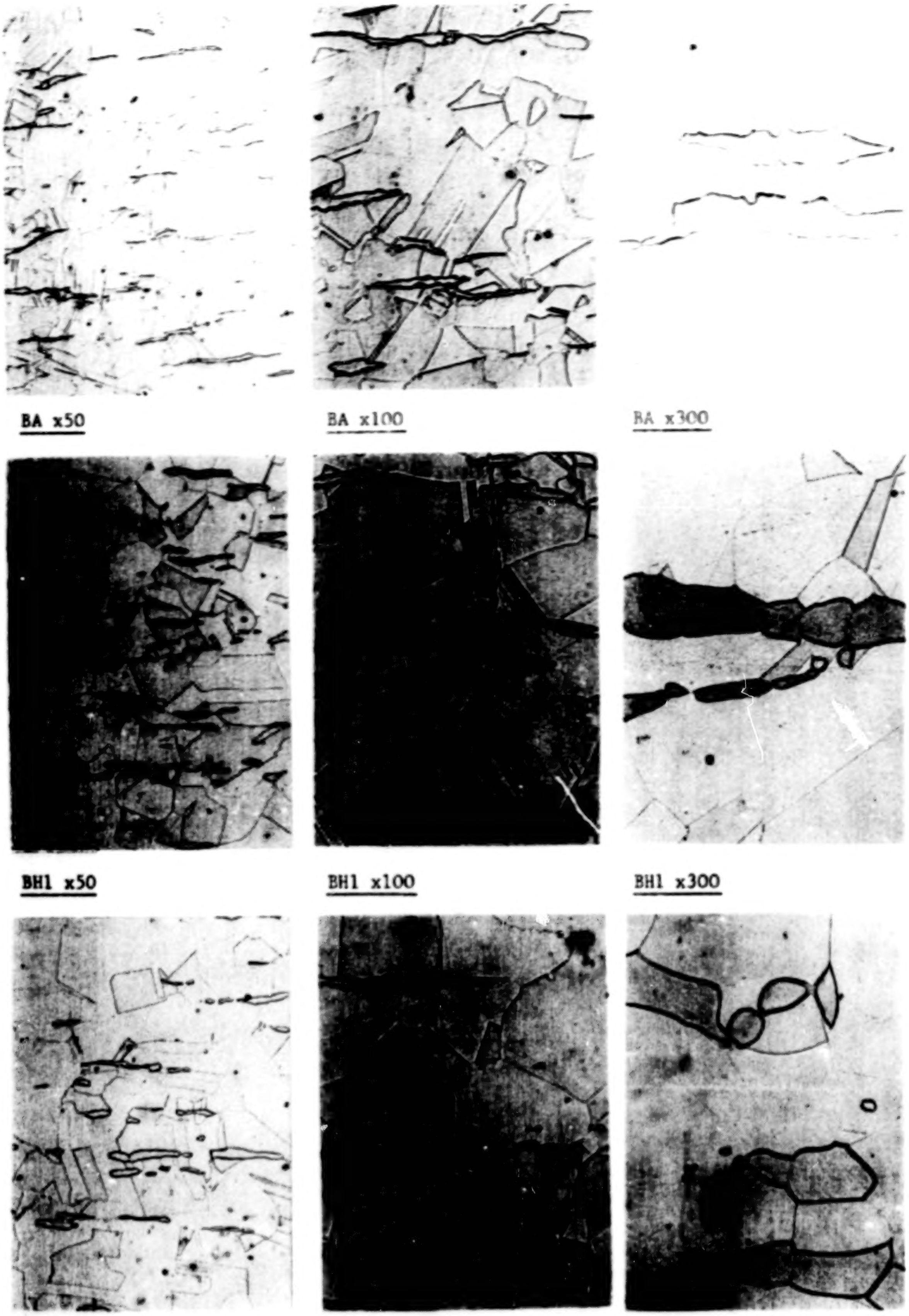
WH1 x300

WH2 x50

WH2 x100

WH2 x300

Figure 19.- Sample W. A = as received; H1 = 2200°F, 2 hr; H2 = 2200°F, 8 hr. (From ref. 1.)



BA x50

BA x100

BA x300

BH1 x50

BH1 x100

BH1 x300

BH2 x50

BH2 x100

BH2 x300

Figure 20.- Sample B. A = as received; H1 = 2200°F, 2 hr; H2 = 2200°F, 8 hr. (From ref. 1.)

CRYOGENIC MATERIALS SELECTION, AVAILABILITY, AND COST CONSIDERATIONS

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Material selection for cryogenic models is similar to that for conventional models, with the added requirements of fracture toughness and alloy phase stability. The requirements for close tolerances and surface finish dictate the use of dimensionally stable material. To ensure required properties, materials should be ordered to tight specifications, with guaranteed properties if possible (fig. 1). Surface protection of finished models may be required for highly loaded models. Material cost, while high compared to common alloys, should not be a major selection factor for cryogenic wind tunnel models.

At Langley, all basic alloy groups have been considered for cryogenic models, but only the iron-base (steels) and aluminum alloys appear to be viable candidates (fig. 2). Because of the high loads expected in the National Transonic Facility (NTF), steels have received the most attention. The divergent requirements of high strength and high toughness are illustrated by the technology trend line for commercial alloys (fig. 3 and ref. 1). As loads are increased, the number of available alloys is severely constrained by toughness requirements. The material selection for the Pathfinder I model was further restrained by delivery schedules, which prompted a consideration of several alloy groups before NITRONIC 40 was selected (fig. 4 and ref. 2).

Figure 5 lists alloys currently under study at Langley, with particular emphasis on austenitic A-286 and martensitic Vascomax 200 and PH 13-8 Mo. The ferritic Fe-12 Ni alloy developed at NASA Lewis Research Center appears to be a promising future material. The Fe-12 Ni alloys have demonstrated yield strengths in excess of 200 ksi with fracture toughness K_{Ic} = 200 ksi-in$^{1/2}$ at 77 K (fig. 6). In preliminary tests at Langley, the Fe-12 Ni alloys have demonstrated cryogenic stability superior to Vascomax 200 with relative ease of machinability. Langley is currently procuring two 7000-lb (14,000 lb total) melts of Fe-12 Ni in various-size plate and bar stock. If the same properties demonstrated in small experimental melts can be duplicated in these large melts, Fe-12 Ni should become the preferred material for cryogenic models.

Multistep heat treatment to refine the grain size appears to be a viable processing technique to improve the toughness of many existing high-strength materials (fig. 7). These techniques were developed at the University of California at Berkeley by J. W. Morris (ref. 3). Recent experiments at Langley using a modified version of this heat treatment have improved the CVN (Charpy V-notch) impact strength of HP 9-4-20 steel from 14 ft-lb to 39 ft-lb at 77 K. This is an improvement of 179 percent, with only a 25-percent loss in tensile strength. Langley is continuing this work to include other high-strength alloys such as Vascomax 200 and HP 9-4-30.

Langley experience to date has shown long lead times for all candidate cryogenic model materials (fig. 8). Lead times of 26 to 52 weeks are not unusual for quality material purchased to tight specifications (fig. 9). Material cost, although small compared to total model cost, will approach $10/lb for quality material (fig. 10). Langley experience with the Pathfinder I model has demonstrated the necessity for high-quality material even at premium prices.

All the preferred materials listed in figure 11 were selected for their combinations of cryogenic strength and toughness, except NITRONIC 60. Although it is not considered as a primary construction material, NITRONIC 60 is included for its nongalling characteristics, which make it suitable for balance mounts, sting nuts, and other close-tolerance fits where galling may be a problem.

Composite materials for cryogenic models have received low priority at Langley, with the work limited to "proof of concept" and conceptual designs only (fig. 12). An extensive data base was developed for epoxy/glass laminates during the NTF fan blade program, but no work has been done to date on advanced composites. The NTF fan blade experience has pointed out the necessity for an extensive testing and qualification program before any composite material can be considered for primary structural use.

Langley's test program has identified several commercial solder alloys that are acceptable for cryogenic models. Bag-3, Eutectic 155, and Eutectic 157 have been the most successful; however, the trend is for lower temperature solders to be more difficult to use due to reduced wettability (fig. 13). A program has been initiated at Langley to identify additional low-temperature solders. Several epoxy-based adhesives have been found to be acceptable for cryogenic service, but they all require either long cure times (24 hours plus) or elevated-temperature cures. Currently there are no completely acceptable quick-cure filler materials. Experience to date in the Langley 0.3-Meter Transonic Cryogenic Tunnel has shown that polyester/plastic fillers can be used to fill gaps and screw heads if used in thin films. Langley currently has a program to identify additional fillers; however, requirements for quick cure (15 minutes or less) and cold model surfaces (40° to 60°F) may not be attainable (fig. 14). Of all the basic material requirements for cryogenic models, filler materials appear to pose the most difficult problem.

REFERENCES

1. Tober, R. L.: Materials for Cryogenic Wind Tunnel Testing. National Bureau of Standards, NBSIR 79-1624, 1980.

2. Hudson, C. Michael: Material Selection for the Pathfinder I Model. Cryogenic Technology, NASA CP-2122, Part II, 1980, pp. 423-441.

3. Jin, Sungho; Hwang, S. K.; and Morris, J. W., Jr.: Composite Fracture Toughness of an Ultra-Fine-Grained Fe-Ni Alloy at Liquid Helium Temperature. Metallurgical Transactions, vol. 6A, August 1975, pp. 1569-1575.

I MECHANICAL PROPERTIES
   1. YIELD AND ULTIMATE STRENGTH
   2. TOUGHNESS (25 FT. LBS. CVN, K_{1c} = 85 KSI $\sqrt{\text{IN.}}$ @ 77 K)
   3. ELASTIC MODULUS

II THERMAL PROPERTIES
   1. ALLOY PHASE STABILITY
   2. EXPANSION COEFFICIENT
   3. THERMAL CONDUCTIVITY

III FABRICATION
   1. MACHINING (CLOSE TOLERANCES, SURFACE FINISH, MACHINING RATES)
   2. DIMENSIONAL STABILITY (MACHINING INDUCED STRESSES, WORK HARDENING, HOT-WORK INDUCED STRESSES)
   3. HOT-WORK FABRICATION (WELDING, BRAZING, CASTING, HEAT TREATMENT)

IV AVAILABILITY
   1. AS SPEC. DELIVERY
   2. DELIVERY DATE

V CORROSION RESISTANCE
   1. STAINLESS ALLOYS AVAILABLE FOR LOW/MEDIUM STRENGTH REQUIREMENTS
   2. SURFACE PROTECTION REQUIRED FOR HIGH STRENGTH ALLOYS

VI COST
   1. \$5-\$10/LB; TIGHT SPECS AND QUALITY ASSURANCE CAN INCREASE COST 50-75%
   2. MATERIAL COST SMALL COMPARED TO TOTAL MODEL COST (5% OR LESS)

Figure 1.- Metallic material selection for cryogenic models.

I IRON BASE (STEELS)
   1. BEST MATCH FOR RESEARCH REQUIREMENTS
   2. EXTENSIVE CRYO DATA BASE
   3. LARC WORK CONCENTRATED ON (BUT NOT LIMITED TO) STEELS

II NICKEL BASED SUPERALLOYS
   1. LIMITED CRYO DATA
   2. FABRICATION DIFFICULTY
   3. LIMITED AVAILABILITY AND HIGH COST

III ALUMINUM ALLOYS
   1. 5000 & 6000 SERIES ACCEPTABLE FOR CRYO USE
   2. LARC EXPERIENCE WITH 0.3-M TCT
   3. LOW STRENGTH & MODULUS

IV COPPER BASED ALLOYS
   1. SOME BECU ALLOYS ACCEPTABLE BUT DATA BASE LIMITED
   2. COLD WORK MAY PRODUCE BRITTLE FRACTURE
   3. LIMITED FABRICATION EXPERIENCE

V TITANIUM
   1. FABRICATION DIFFICULTIES
   2. LONG LEAD TIMES

Figure 2.- Basic alloy groups.

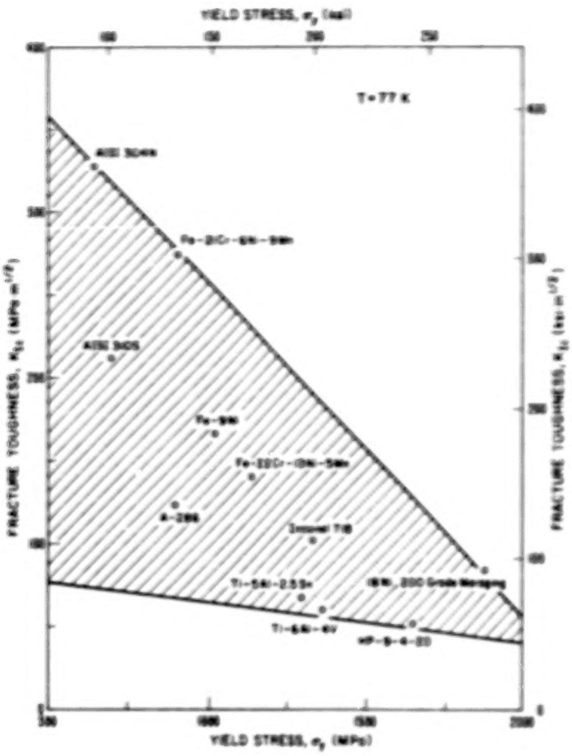


Figure 3.- Toughness versus strength trend for structural metals at 77 K. (From ref. 1.)

MATERIAL	CONDITION	σ_{yp}, ksi		σ_u, ksi		C_{VN}, ft-lb		K_{Ic}, ksi-in$^{1/2}$	
		RT	140° R	RT	140° R	RT	140° R	RT	140° R
18 Ni STEEL	250	250	320	260	330	20	10	100	40
18 Ni STEEL	200	205	27[illegible]	[illegible]10	280	35	25	170	80
AF 1410 STEEL	DOUBLE AUSTENITIZED AND AGED	230	250	250	260	40	30	125	--
SPECIAL 9% Ni STEEL	NORMALIZED & TEMPERED QUENCHED & TEMPERED STRESS RELIEVED	105	145	115	175	--	80	--	160
A286 STAINLESS STEEL	SOLUTION TREATED AND AGED	100	120	160	215	55	50	120	110
NITRONIC 40 STAINLESS STEEL	ANNEALED	70	150	[illegible]10	200	200	65	--	165
PH 13-8 Mo STAINLESS STEEL	H1150M	85	145	130	175	80	60	--	--
INVAR	ANNEALED	40	90	80	125	220	50	--	--
INCONEL 718	SOLUTION TREATED AND AGED	150	175	185	235	20	20	90	100
INCONEL X750	SOLUTION TREATED AND AGED	110	125	180	215	35	35	--	100
Ti-6Al-4V ELI	ANNEALED	130	190	135	205	20	10	90	55
Ti-5Al-2.5Sn ELI	ANNEALED	105	175	120	180	25	10	90	65

Figure 4.- Nominal tensile and toughness properties of materials considered for the Pathfinder I model. (From ref. 2.)

I AUSTENITIC
  1. 300 SERIES STAINLESS STEELS
  2. NITRONIC STAINLESS STEELS
  3. A-286

II MARTENSITIC
  1. VASCOMAX 200
  2. PH 13-8 Mo STAINLESS STEEL
  3. HP 9-4-20

III FERRITIC
  1. 9 Ni (ASTM A353)
  2. Fe-12 Ni (LEWIS RESEARCH CENTER)

Figure 5.- Alloys under current study at Langley.

1. HIGH STRENGTH/TOUGHNESS CRYOGENIC ALLOYS DEVELOPED AT LeRC
2. 200 KSI YIELD AND K_{1c} = 200 KSI $\sqrt{\text{IN.}}$ AT 77 K
3. STABLE PHASE ALLOY
4. SIMPLE ALLOY SYSTEM (NO SCARCE, STRATEGICALLY CRITICAL INGREDIENTS)
5. LaRC CURRENTLY PROCURING LARGE MELT (14,000 LBS.)

Figure 6.- Fe-12 Ni alloys.

1. TECHNIQUE DEVELOPED AT UNIVERSITY OF CALIFORNIA AT BERKELEY

2. LaRC CURRENTLY STUDYING GRAIN REFINEMENT OF 9Ni AND HP 9-4-20

3. STEEL INDUSTRY CURRENTLY DEVELOPING GRAIN REFINEMENT HEAT TREATS FOR VASCOMAX 200 AND AF-1410

Figure 7.- Grain refinement heat treating.

VASCOMAX 200	6/81 - 12/81	26 WEEKS
PH 13-8 Mo	7/80 - 10/81	65 WEEKS
A-286	10/81 - 2/82	17 WEEKS
A-286	CURRENT QUOTE (JAPAN)	26 WEEKS?

Figure 8.- Recent lead times at Langley for procurement of cryogenic model material.

13-26 WEEKS IF IN CURRENT PRODUCTION

26-52 WEEKS IF NOT IN PRODUCTION

50-75% INCREASE IN DELIVERY DATE FOR TIGHT SPECS AND INSPECTION

Figure 9.- Lead time minimums for procuring material for cryogenic models.

NITRONIC 40	$3.00/LB.
VASCOMAX 200	$8.71/LB.
A-286	$7.75/LB.
PH 13-8 Mo	$9.54/LB.

Figure 10.- Langley material cost (three 10K-lb lots).

AUSTENITIC	MARTENSITIC	FERRITIC
A-286	VASCOMAX 200	9Ni
NITRONIC 60	PH-13-8 Mo	
	HP 9-4-20	

PROMISING FUTURE MATERIALS

1. Fe - 12 Ni STEELS
2. GRAIN REFINED HIGH STRENGTH ALLOYS
3. POWDERED METAL ALLOYS

AVAILABILITY/LEAD TIME

1. ALL PREFERRED MATERIALS CURRENTLY AVAILABLE
2. TIGHT SPECS AND INSPECTION A MUST TO INSURE MATERIAL PROPERTIES
3. LONG LEAD TIME FOR ALL ALLOY GROUPS
4. MATERIAL SELECTION SHOULD BE MADE EARLY IN PROGRAM

Figure 11.- Preferred model materials as of May 1982.

I COMPOSITE CRYO MODELS CURRENTLY LOW PRIORITY AT LaRC

II EXTENSIVE CRYO DATA BASE FOR EPOXY/GLASS LAMINATES (NTF FAN BLADES)

III COMPOSITE MODEL DESIGN/FAB

1. 2D-AIRFOIL "PROOF OF CONCEPT" MODEL CONSTRUCTED FOR 0.3-M TCT
2. 3D-WING FOR NTF (CONCEPTUAL DESIGN)

IV COMPOSITE EFFORT TO INCREASE AS TIME AND RESOURCES BECOME AVAILABLE

Figure 12.- Composite materials.

I. CRYO SUITABILITY PROGRAM

	TYPE	TEMP(°F)	WETTABILITY
1.	BAG-3	1270	GOOD
2.	EUTECTIC-155	725	FAIR
3.	EUTECTIC-157	425	POOR

II. CURRENT PROGRAM TO IDENTIFY LOW TEMP SOLDERS WITH HIGH WETTABILITY

1. INDIUM ALLOYS
2. LEAD/SILVER ALLOYS

Figure 13.- Solders.

I. STRUCTURAL ADHESIVES

1. HYSOL EA-934 (FILLED EPOXY)
2. CYANAMID FM-1000 (NYLON/EPOXY FILM)
3. EPON 828 30%/VERSIMID 70%(EPOXY/POLYAMIDE)

II. FILLER MATERIALS

1. 0.3-M TCT (<1/8" THICK)
    - A. WHITE LIGHTNING, 15-20 MIN. (POLYESTER/PLASTIC)
    - B. PLASTIC PADDING, 5-10 MIN. (POLYESTER/PLASTIC)
    - C. DEVCON F, 2 HR. + (ALUMINUM/EPOXY)
2. CURRENT PROGRAM TO IDENTIFY ADDITIONAL FILLERS, IF NECESSARY DEVELOP NEW ONES

Figure 14.- Adhesives and fillers.

DEVELOPMENT OF TOUGH, STRONG, IRON-BASE ALLOY FOR CRYOGENIC APPLICATIONS

Joseph R. Stephens
NASA Lewis Research Center
Cleveland, Ohio

An experimental program was conducted at NASA Lewis Research Center to develop an iron-base alloy that combines the normally divergent properties of high toughness and high strength at cryogenic temperatures. Specifically, alloy properties were sought which at -196°C would exhibit a fracture toughness of 220 MPa-m$^{\frac{1}{2}}$ (200 ksi-in.$^{\frac{1}{2}}$) with a corresponding yield strength of 1.4 GPa (200 ksi). Early work showed that high toughness could be achieved in Fe-12Ni alloys containing reactive metal additions such as Al, Nb, Ti, and V. Further research emphasized strengthening of these tough alloys by thermomechanical processing and the addition of Cu. Results showed that high strength and high toughness could be achieved in a single alloy at temperatures as low as -196°C. An alloy with composition Fe-12Ni-0.5Al-2Cu exhibited a yield strength of 1.65 GPa with a corresponding fracture toughness of 220 MPa-m$^{\frac{1}{2}}$ at -196°C. Strengthening due to Cu additions to the Fe-12Ni base alloys results primarily from precipitation of Cu-rich ε particles approximately 20 nm in diameter. Strengthening mechanisms are discussed in terms of an elastic modulus hardening model and are supported by transmission electron microscopy examinations of selected test specimens.

TOUGHNESS/STRENGTH MODELING - I

FACTOR	TOUGHNESS	STRENGTH
CRYSTAL STRUCTURE - FCC	↑	↓
- BCC	↓	↑
ALLOYING - SUBSTITUTION	↓	↑
- INTERSTITIAL	↓	↑
- PARTICLES - ACTIVE	↓	↑
- PASSIVE	↑	↑
METALLURGICAL STRUCTURE		
- GRAIN SIZE	↑	↑
- SUBGRAIN SIZE	↑	↑
- TMP	↑	↑
- HEAT TREATMENT	↑	↑

TOUGHNESS/STRENGTH MODELING - II

$$\Delta\sigma = \sigma_0 + K\pi^{-\frac{1}{2}}$$

$$\pi = \pi_p, \ \pi_c, \ \pi_d$$

ALLOYING
TMP
HEAT TREATMENT

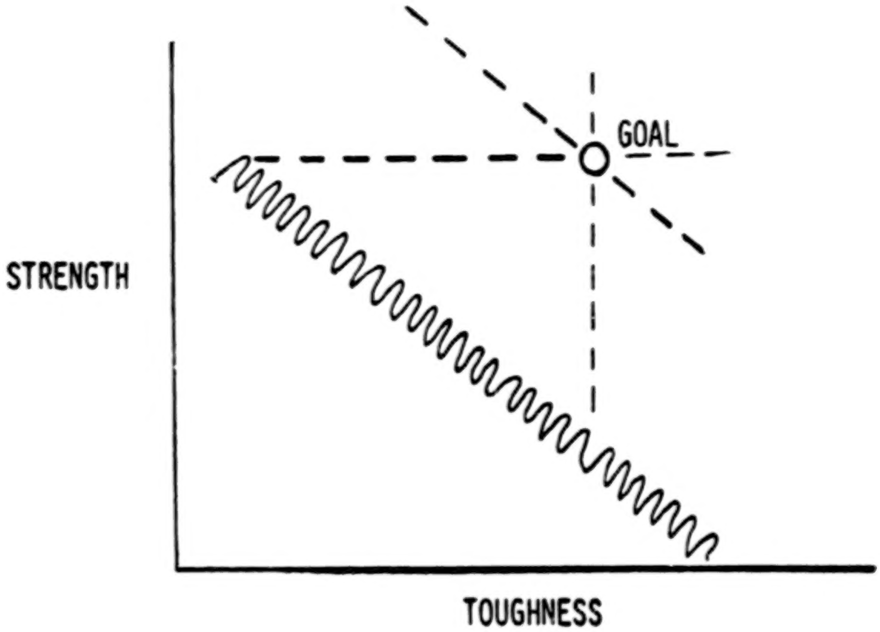
$$\Delta\sigma_E = \frac{K\,Gb}{\pi_p}\left(1 - \frac{E^2_{SOFT}}{E^2_{HARD}}\right)^{\frac{1}{2}}$$

COPPER IN IRON

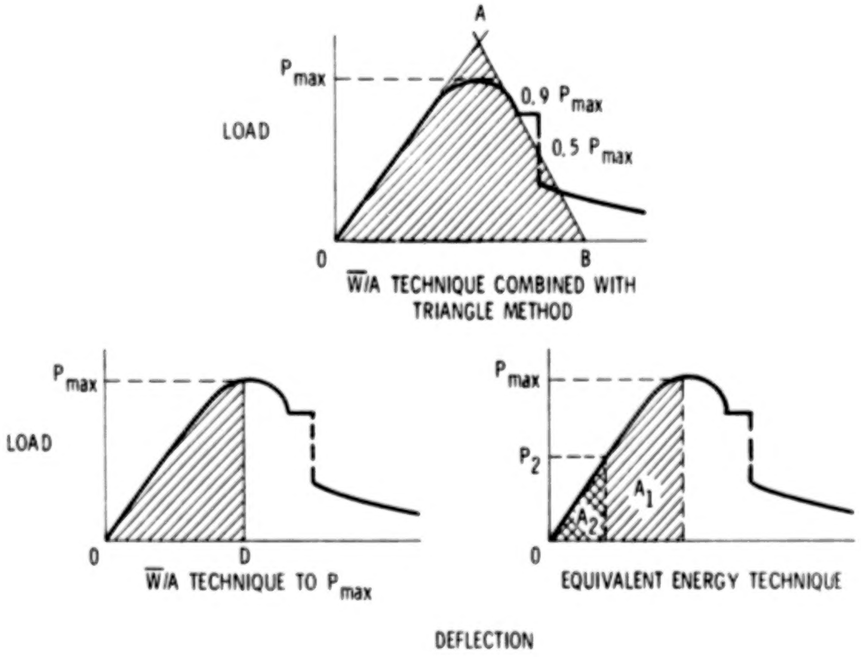
$\Delta K_{ICD} \propto \pi_p$, SIZE, SHAPE, MODULUS

PURITY
COPPER IN IRON

PRACTICAL AND PHILOSOPHICAL CONSIDERATIONS



LOAD-DEFLECTION CURVES ILLUSTRATING AREAS UNDER CURVE THAT WERE MEASURED IN DETERMINING FRACTURE TOUGHNESS OF SMALL SPECIMENS



$\overline{W}/A$ TECHNIQUE COMBINED WITH TRIANGLE METHOD

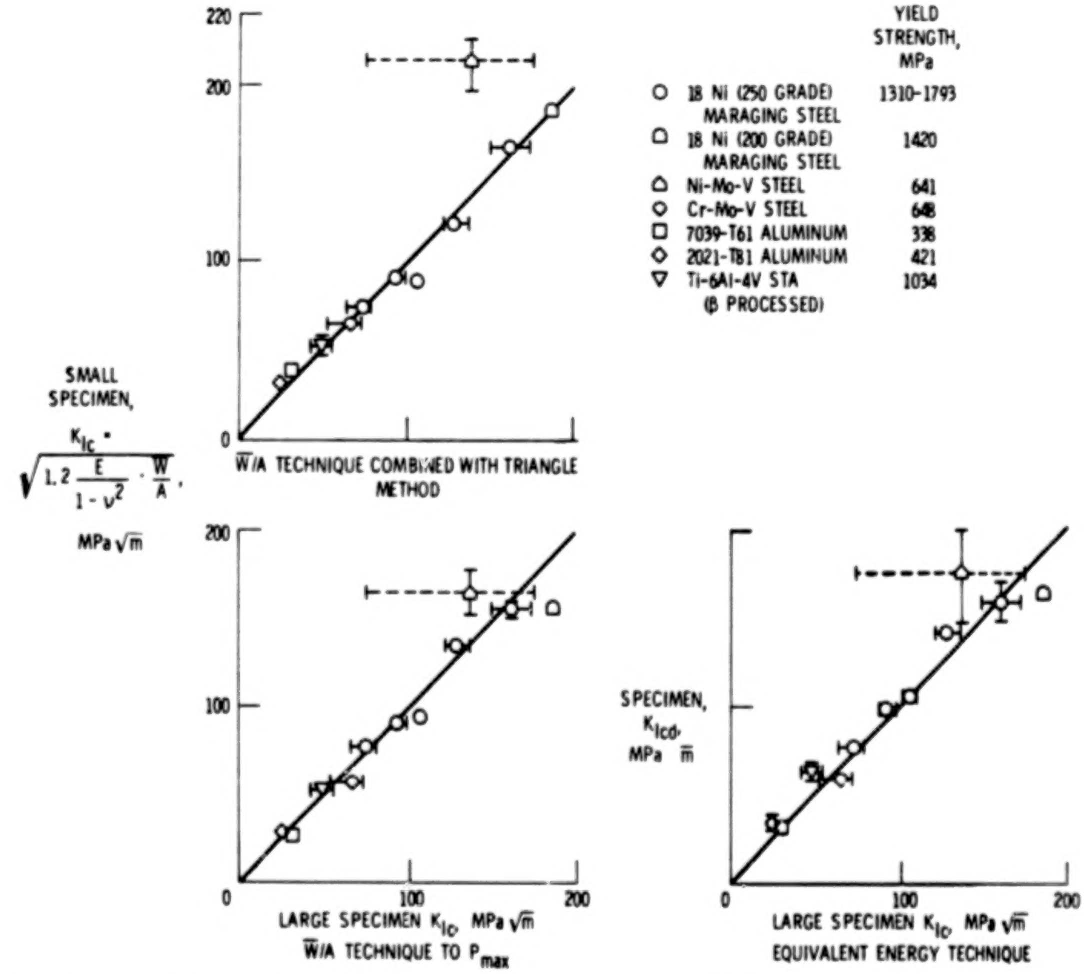
$\overline{W}/A$ TECHNIQUE TO P_{max}

EQUIVALENT ENERGY TECHNIQUE

$$K_{ICD} = \frac{SP\left(\frac{A_1}{A_2}\right)^{1/2} f\left(\frac{a}{w}\right)}{BW^{3/2}}$$

S	SPAN OF THREE-POINT BEND FIXTURE
P	ANY LOAD ON LINEAR PORTION OF LOAD DISPLACEMENT CURVE
A_1	AREA UNDER CURVE TO MAXIMUM LOAD
A_2	AREA UNDER CURVE TO P
$f(a/w)$	VALUE OF POWER SERIES FOR a/w
B	SPECIMEN THICKNESS
a	CRACK LENGTH
W	SPECIMEN WIDTH

CORRELATION OF SMALL SPECIMEN FRACTURE TOUGHNESS WITH LARGE SPECIMEN VALID K_{1c} VALUES AT 25°C*



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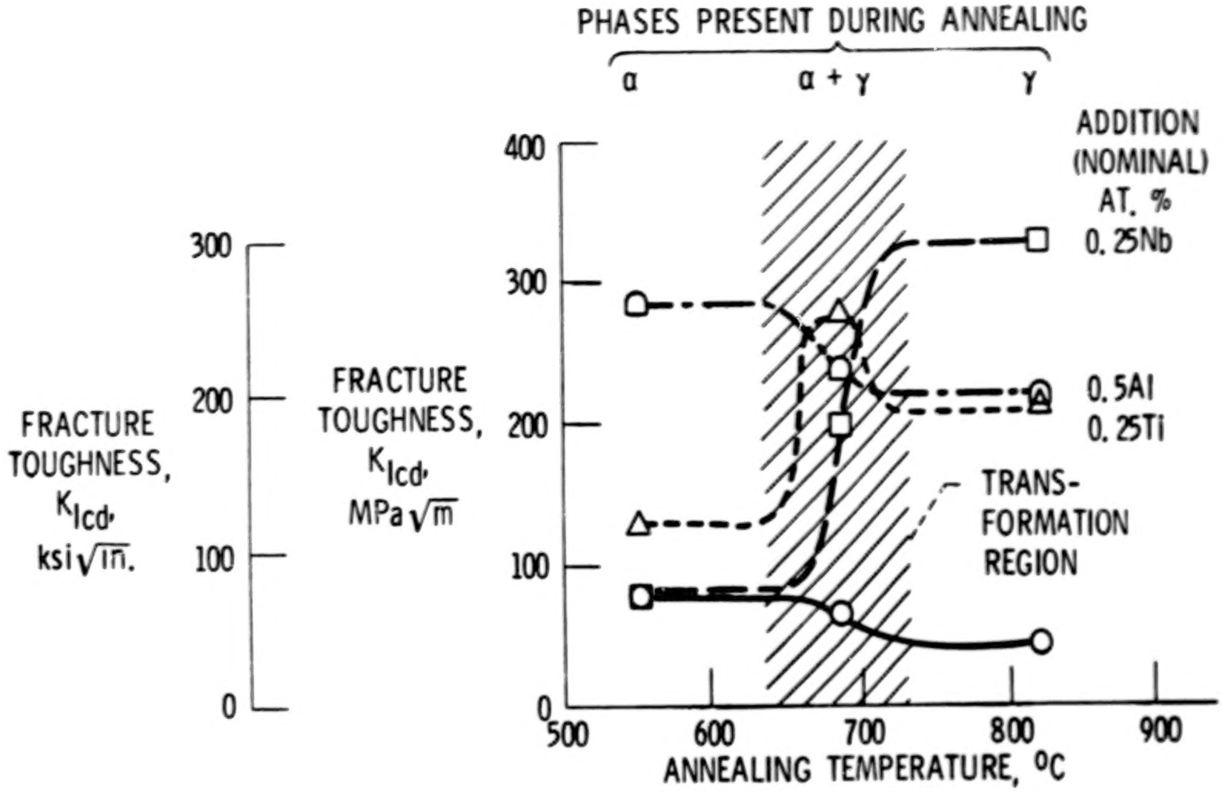
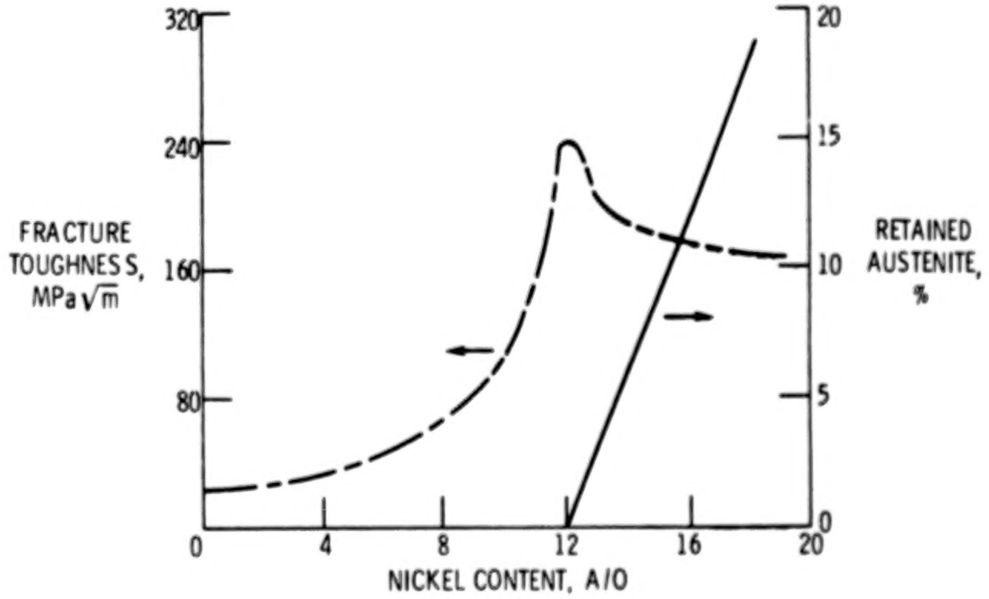
*From Witzke, W. R.; and Stephens, J. R.: Comparison of equivalent energy and energy per unit area ($\overline{W}$/A) data with valid fracture toughness data for iron, aluminum, and titanium alloys. J. of Testing and Eval., vol. 6, no. 1, Jan 1978, pp. 75-79.

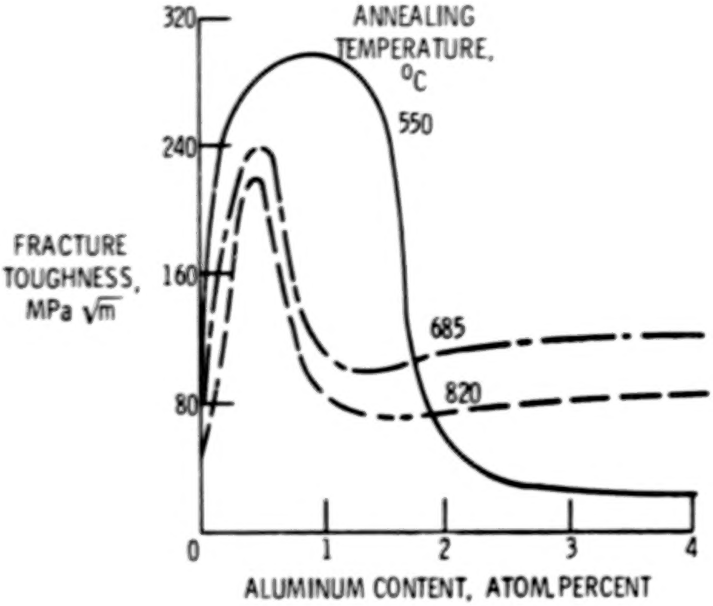
TOUGHNESS VS ANNEALING TEMPERATURE



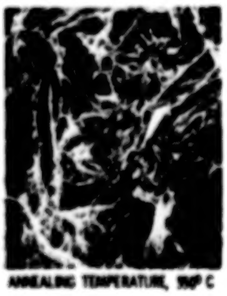
EFFECT OF NICKEL CONTENT ON FRACTURE TOUGHNESS AND RETAINED AUSTENITE OF Fe-Ni-0.5Al ALLOYS ANNEALED AT 550° C AND TESTED AT -196° C



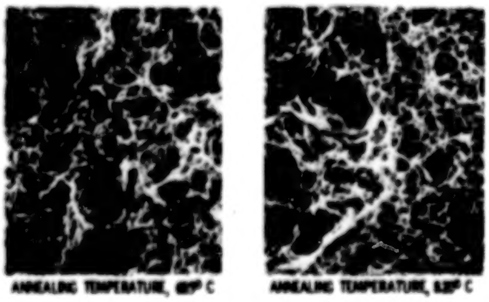
EFFECT OF ALUMINUM CONTENT ON FRACTURE TOUGHNESS OF Fe-12Ni-Al ALLOYS AT -196° C



FRACTOGRAPHS OF FRACTURE TOUGHNESS SPECIMENS OF Fe-12Ni-0.5Al TESTED AT -196°C X500



ANNEALING TEMPERATURE, 550° C

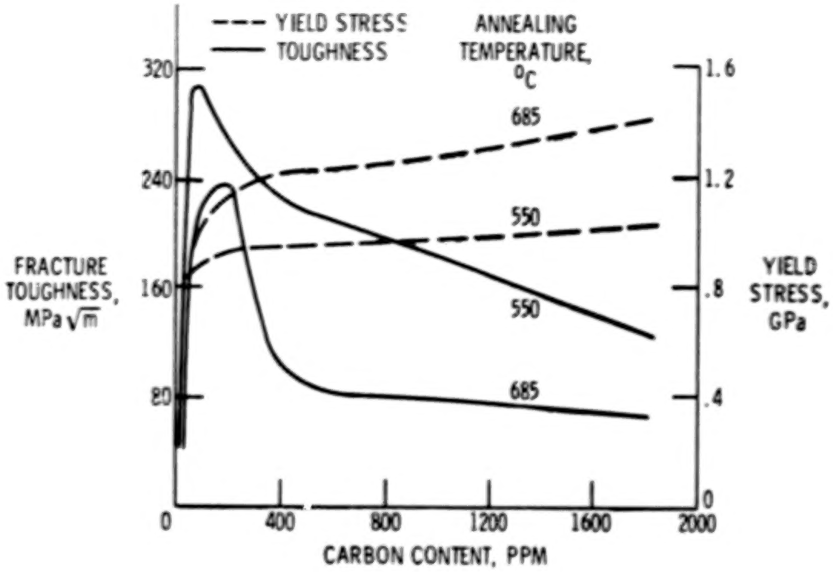


ANNEALING TEMPERATURE, 685° C

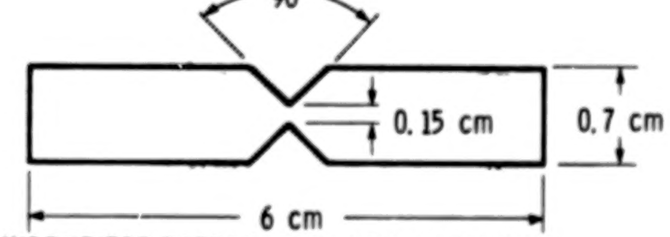
ANNEALING TEMPERATURE, 820° C

From Witzke, Walter R.; and Stephens, Joseph R.: Effect of minor reactive metal additions on fracture toughness of iron-12-percent-nickel alloy at -196° and 25°C. NASA TN D-8232, 1976.

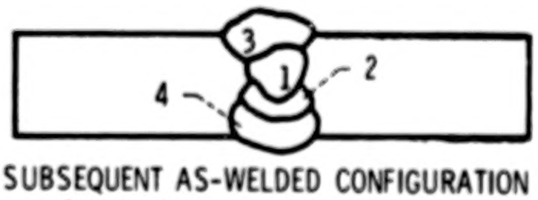
EFFECT OF CARBON CONTENT ON FRACTURE TOUGHNESS AND YIELD STRESS OF Fe-12Ni-0.5Al ALLOY AT -196° C



GAS-TUNGSTEN ARC (GTA) WELD JOINT

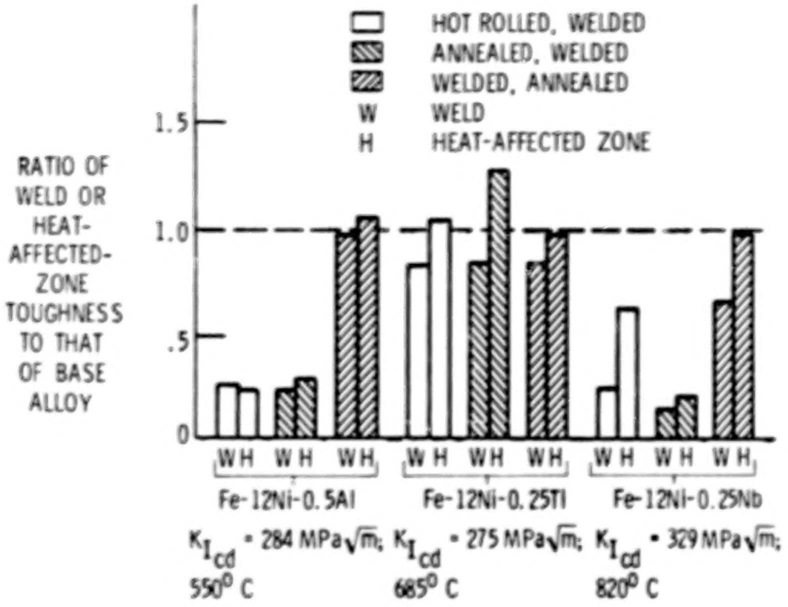


WORKPIECE PREPARATION BEFORE WELDING

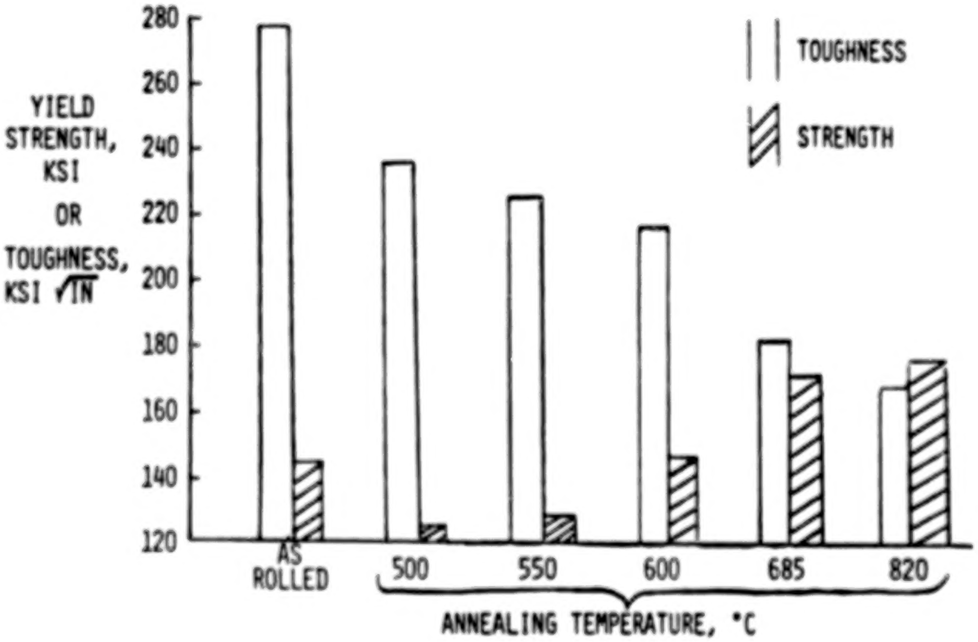


SUBSEQUENT AS-WELDED CONFIGURATION SHOWING WELD-PASS SEQUENCE

COMPARISON OF WELDED TOUGHNESS WITH BASE ALLOY AT -196° C



TOUGHNESS/STRENGTH PROPERTIES OF Fe-12Ni-0.5Al AT -196°C (350-LB INGOT)*



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*From Bhat, G. K.: Evaluation of mechanical properties of electroslag-refined Fe-12Ni alloys. NASA CR-159394, 1978.

ESTIMATED COST

7000 LB. INDUCTION MELT

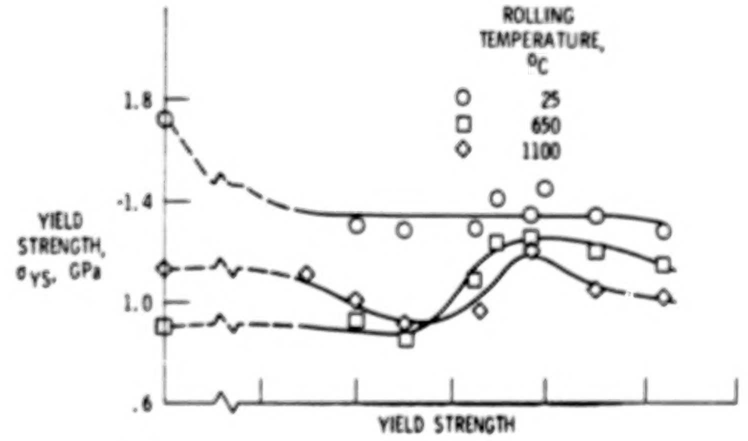
ESR REMELT

FORGE

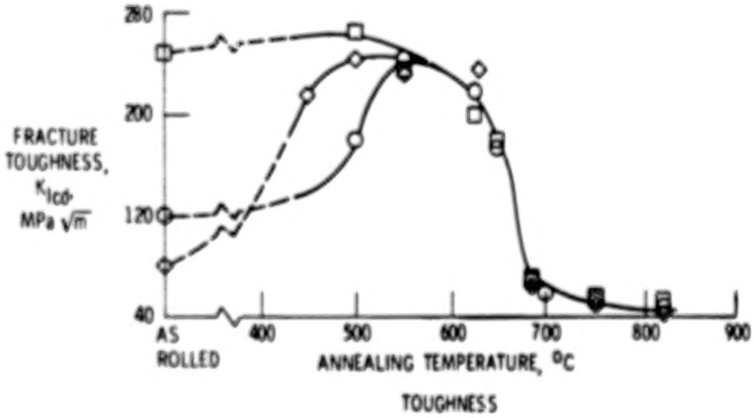
ROLL TO PLATE

≈$4.00/LB

EFFECTS OF THERMOMECHANICAL PROCESSING ON STRENGTH AND TOUGHNESS OF Fe-12Ni-0.5Al ALLOYS AT -196° C

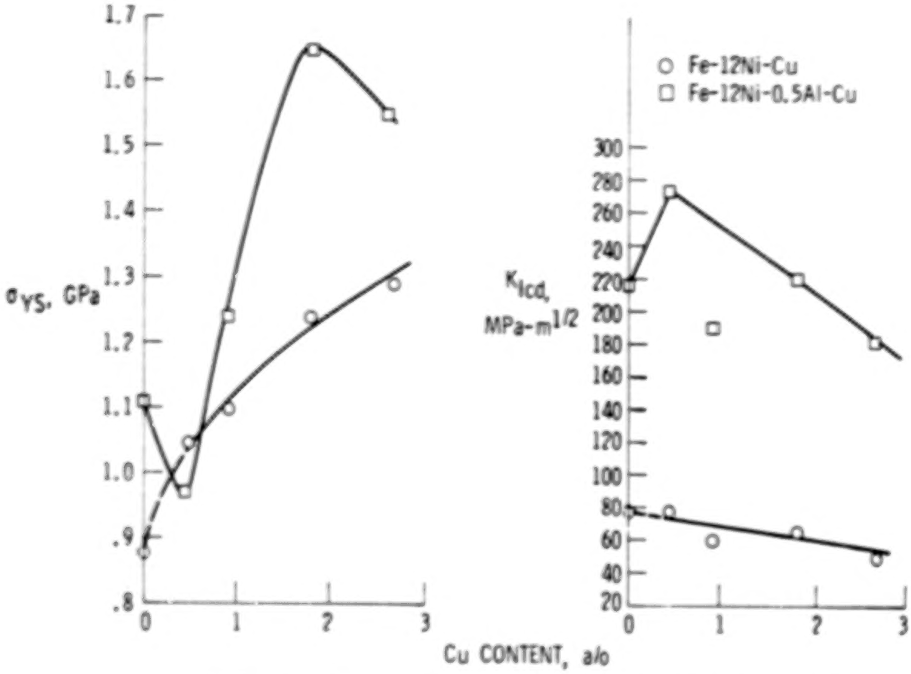


YIELD STRENGTH



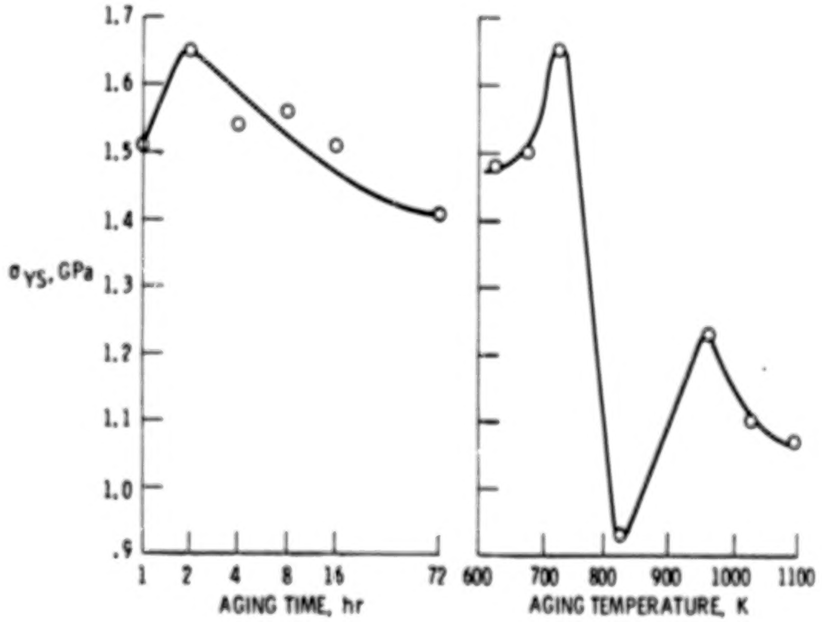
TOUGHNESS

STRENGTH AND TOUGHNESS OF Fe-12Ni-Cu AND Fe-12Ni-0.5Al-Cu ALLOYS AT 77 K



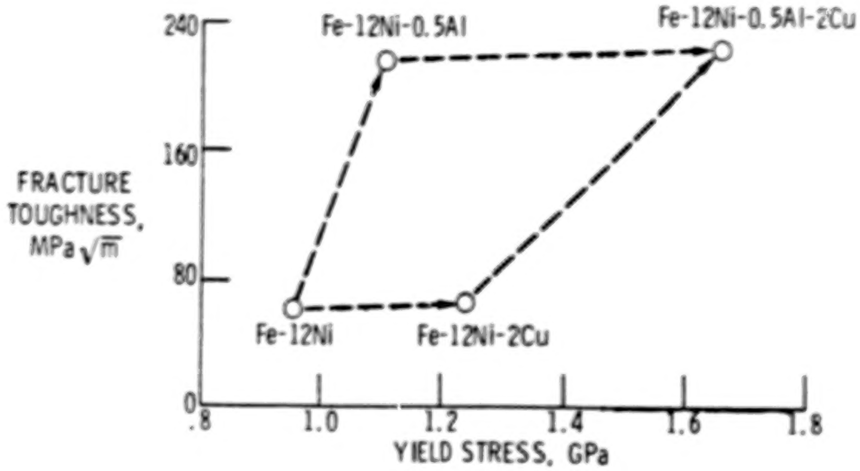
AGED 2 h - 725 K a - YIELD STRENGTH; b - FRACTURE TOUGHNESS

EFFECTS OF AGING CONDITIONS ON 0.2% YIELD STRENGTH OF Fe-12Ni-0.5Al-Cu ALLOY AT 77 K

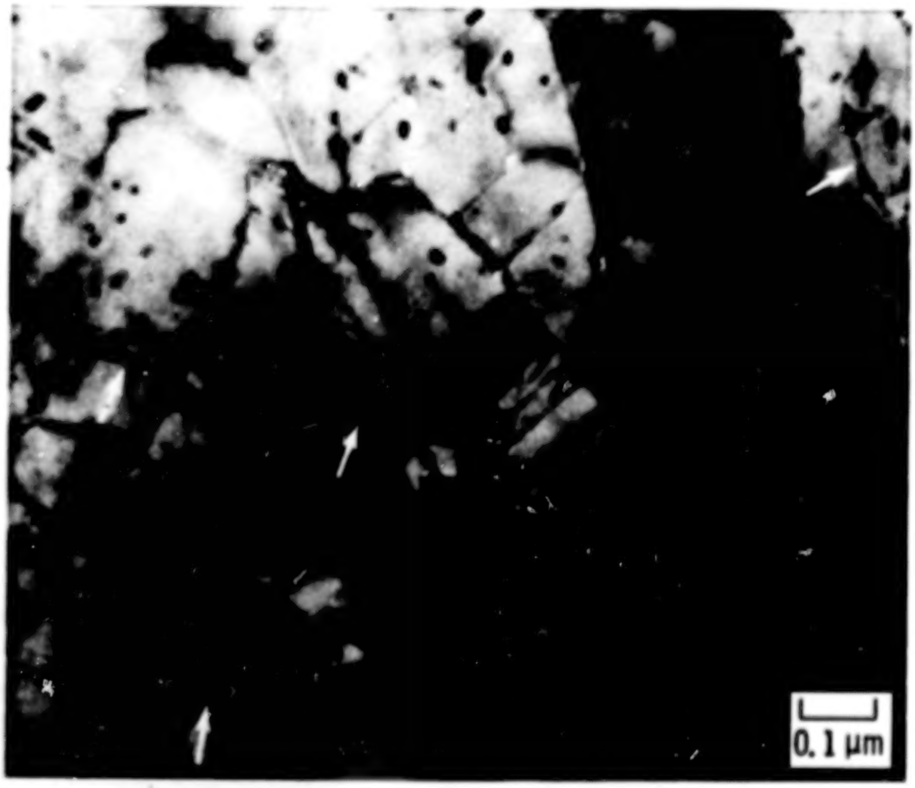


a - AGING TIME AT 725 K; b - AGING TEMPERATURE FOR 2 h

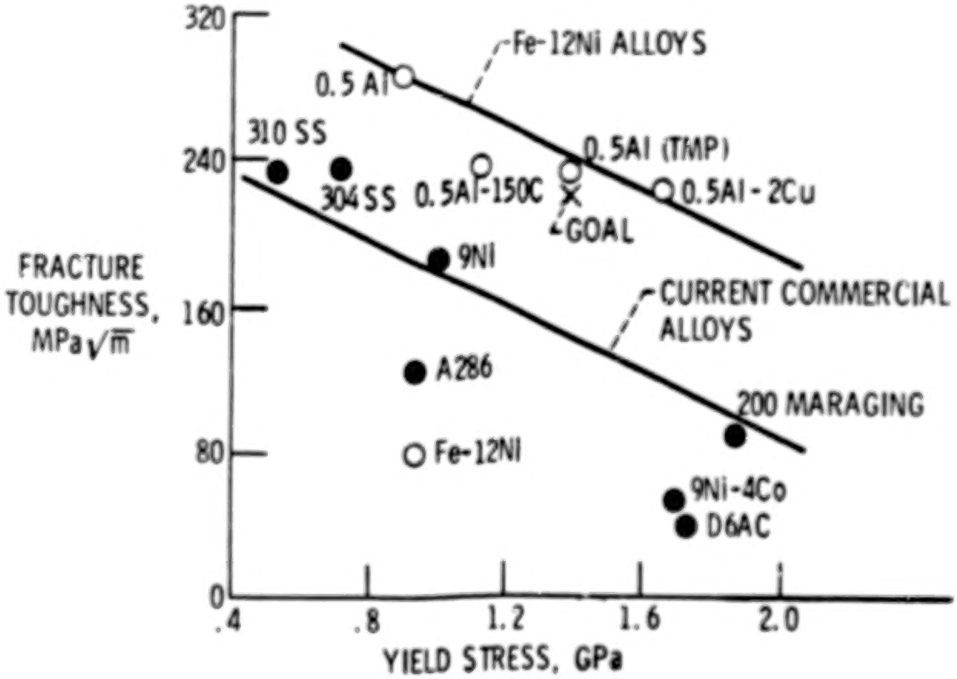
CONTRIBUTIONS OF Al AND Cu TO TOUGHNESS AND STRENGTH OF Fe-12Ni ALLOY ANNEALED AT 450° C AND TESTED AT -196° C



THREADING OF Cu-RICH PARTICLES BY DISLOCATIONS IN Fe-12Ni-0.5Al-2Cu ALLOY



COMPARISON OF FRACTURE TOUGHNESS AND YIELD STRESS OF Fe-12Ni EXPERIMENTAL ALLOYS WITH COMMERCIAL STEELS AT -196° C



WIRE ELECTRIC-DISCHARGE MACHINING AND OTHER FABRICATION TECHNIQUES

William H. Morgan
Douglas Aircraft Co.
Long Beach, California

INTRODUCTION

The new concept of wind tunnel testing in a cryogenic environment, combined with requirements for smaller scale and higher accuracy models utilizing new materials, has created fabrication problems. New methods and techniques need to be investigated. Methods to be discussed will include wire electric-discharge machining (EDM), extrude honing, and a surface measurement device. These methods and procedures were used to fabricate a two-dimensional wing for cryogenic wind tunnel testing.

ELECTRIC-DISCHARGE MACHINING BY WIRE

Electric-discharge cutting is done with a moving wire electrode. The cut track is controlled by means of a punched-tape program and the cutting feed is regulated according to the progress of the work. Electric-discharge machining involves no contact with the work piece, and no mechanical force is exerted. With the electrothermal removal of material, the hardness of the electrically conductive work piece is unimportant. Deionized water is used as a dielectric to flush the particles away from the work piece.

Wire EDM cutting rates can be in excess of 5 sq. in. per hour in tool steel. A cutting tolerance of ±0.0001 in. can be held, producing an excellent surface finish for easy hand finishing or other methods. In some cases the wire EDM can replace the conventional EDM, eliminating the requirement of fabricating expensive electrodes.

EXTRUDE HONE

Extrude hone is a process for honing finish-machined surfaces by the extrusion of an abrasive material (silly putty), which is forced through a restrictive fixture. The material will pass by the part and polish the surface to the required finish. This method is a very fast process and can be used on model components. A 10-to-1 ratio of surface finish can be realized; i.e., if you have a 40-rms finish you can expect a 4-rms finish. Special equipment is required to perform this operation.

Extrude hone also has a new concept in surface finish measurement. Instead of moving a fragile stylus across the surface to be measured, a rugged sensor is pressed against it. The sensor probe measures electrical capacitance between the sensor pad and the work piece to determine average roughness over the area covered by the sensor. The environment is not important. The equipment is inexpensive to purchase.

MODEL FABRICATION

The following methods and procedures were used to fabricate a two-dimensional cryogenic wind tunnel model. The material used was NITRONIC 40 in the annealed condition. The part was also thermal-cycled by immersing it in LN2 before and during the fabrication process.

A computer-controlled wire electric-discharge cutter (0.16 brass wire) was used to machine the airfoil shape. An EDM tool was used to cut the internal pockets and instrumentation routing. The electrode material for roughing slots and pockets was graphite EDM #1, which is 100 percent graphite. Electrode material used for finishing slots and pockets was graphite EDM C-3, which is graphite and copper. Settings were 65 V at 3 A.

The model was fabricated in two pieces, with the split line basically on the center line of the airfoil shape except on the leading edge, where the part line was 0.270 in. aft of the leading edge on the bottom side. The internal surfaces were finish cut using the wire cutting methods. The two pieces were then hand fitted together to a zero gap. The top and bottom pieces were mechanically fastened together using screws and pins. The trailing edge was cemented together using EC-2216 cement. The outer contour was cut 0.040 in. full using the EDM wire, and was checked on the Zeiss coordinate measuring tool for warpage or bow in the contour. At this time there was approximately a 0.015-in. bow. This was caused by a static charge created between the wire electrode and the work piece, and was not a problem during the roughing operations.

The model was then disassembled and the internal machining was accomplished using the conventional vertical electrical-discharge machine tool. The model was reassembled and wire cut to finish dimensions by using skim cuts of approximately 0.010 in. until the surface was within 0.010 in. full. Final cuts were made in 0.002-in. increments.

There were some problems with the trailing edge lifting due to the cement failing in some areas. This could have been due to material stress, or to not enough cement. The Zeiss check of the contour was very close to the lofted shape, as close as 0.001 in. The outer surface was hand finished to a 4-rms finish, and was then covered with aluminum tape, both for protection and to provide a surface to start the drill. The orifice holes were laid out on the aluminum tape and drilled using a small precision drill press. Type N jobber drills (0.014 in. diameter) were used. Some of the orifice holes near the leading edge were counter-bored from the inside surface using the EDM tool due to the extreme angle required. The rest of the orifice holes were counter-bored using conventional methods. Pressure tubes were installed using Hysol 9309.

CONCLUDING REMARKS

Total wire EDM time for this model was 486 hours. The wire EDM tool ran automatically 24 hours a day until each phase was complete. The time taken to fabricate this model is estimated to be less than that required for the numerically controlled mill method. The surface finish is better than a numerically controlled finish and requires much less time to hand finish. The time spent hand finishing this model was 1-1/2 days. Hysol EA-934 with NITRONIC powder added was used to fill the attachment holes.

Our experience at this time has shown that the wire EDM method can be used to fabricate a wind tunnel model that will satisfy the critical requirements of a cryogenic environment.

SURFACE FINISH MEASUREMENT STUDIES

E. Clayton Teague
National Bureau of Standards
Washington, DC

NASA and the National Bureau of Standards initiated a project in the fall of 1980 to address any potential new problems that might be imposed on the surface finish requirements for models to be used in the National Transonic Facility (NTF). At the largest Reynolds numbers of which the NTF was to be capable, admissible roughness heights fell below the surface finishes currently specified for models. The objectives of the joint NASA/NBS project were therefore (1) to evaluate the performance of stylus instruments for measuring the topography of NTF model surfaces both for monitoring during fabrication and as an absolute measurement of topography, (2) to measure and characterize the true three-dimensional topography of NTF model surfaces so that their characteristics could be related back to distributed particle surfaces, and (3) to develop a prototype light-scattering instrument which would allow for rapid assessment of the surface finish of a model.

Work to accomplish the first objective has consisted of comparing research-grade and shop-grade stylus measurements of the surface finish of three test specimens fabricated by NASA. Conclusions from this study and the three-dimensional stylus profilometry developed at NBS for the second objective are that the shop-grade instruments can damage the surface of models and that their use for monitoring fabrication procedures can lead to surface finishes that are substantially out of range in critical areas of the leading edges.

Two closely related concerns were raised relative to the issue of surface finishes. First, in interpreting the classical work of Nikarudse (ref. 1), what properties of the surface topography influence the airflow pattern across a surface and what are the curves of allowed values for these new characterizations as a function of Reynolds number? The need for understanding both surface amplitude and wavelength effects was discussed. Second, in connection with the third objective, the capabilities of major surface topography measurement techniques were presented and compared in terms of a wavelength/slope space. The limited spatial wavelength bandwidth capabilities of light-scattering measurements were highlighted. In relation to the measurement needs for NTF model surfaces, it is therefore important, in using this technique or any other, to determine what range of irregularity spacings is of significance for aerodynamic effects.

REFERENCE

1. Schlichting, Hermann (J. Kestin, transl.): Boundary Layer Theory. Fourth ed., McGraw-Hill Book Co., Inc., c.1960.

QUESTIONS

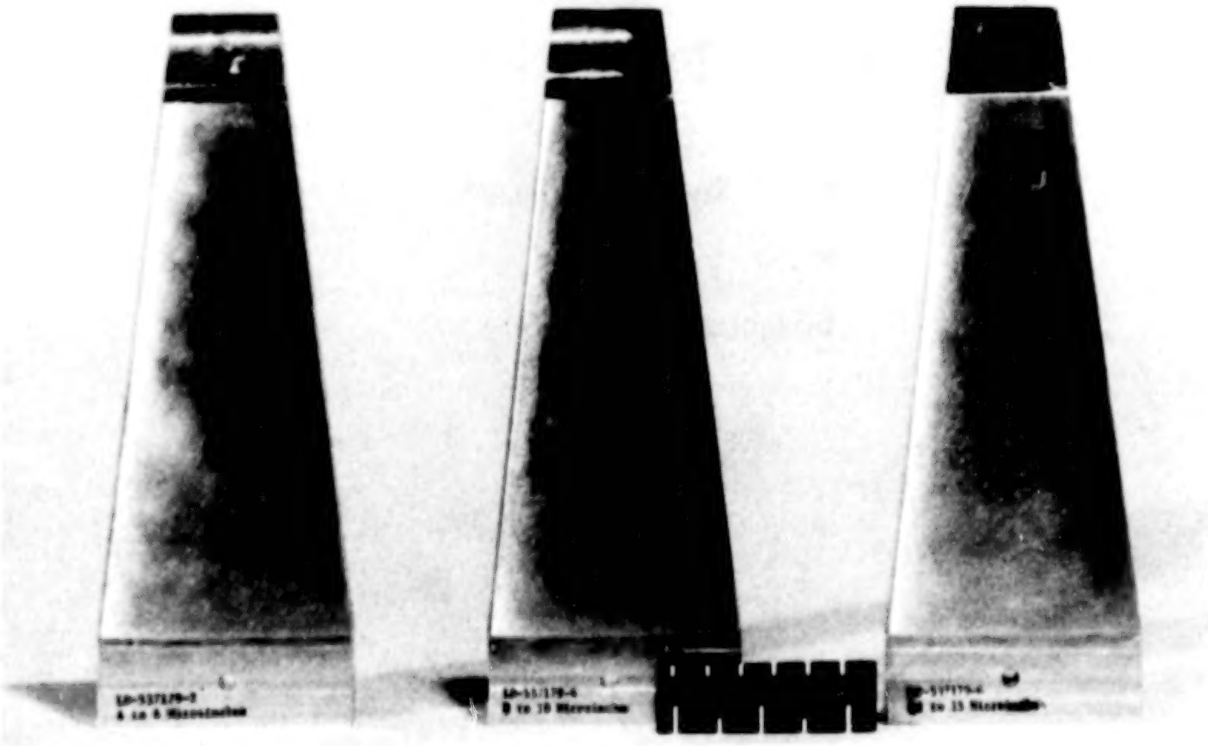
HOW ACCURATELY DOES A STYLUS INSTRUMENT MEASURE THE TOPOGRAPHY OF A SPECIMEN?

WHAT ALTERNATIVES TO THE STYLUS ARE AVAILABLE?

WHAT PROPERTIES OF SURFACE TOPOGRAPHY INFLUENCE AN AIRFLOW PATTERN?

WHAT PARAMETERS BEST CHARACTERIZE THESE PROPERTIES?

SURFACE FINISH SPECIMENS



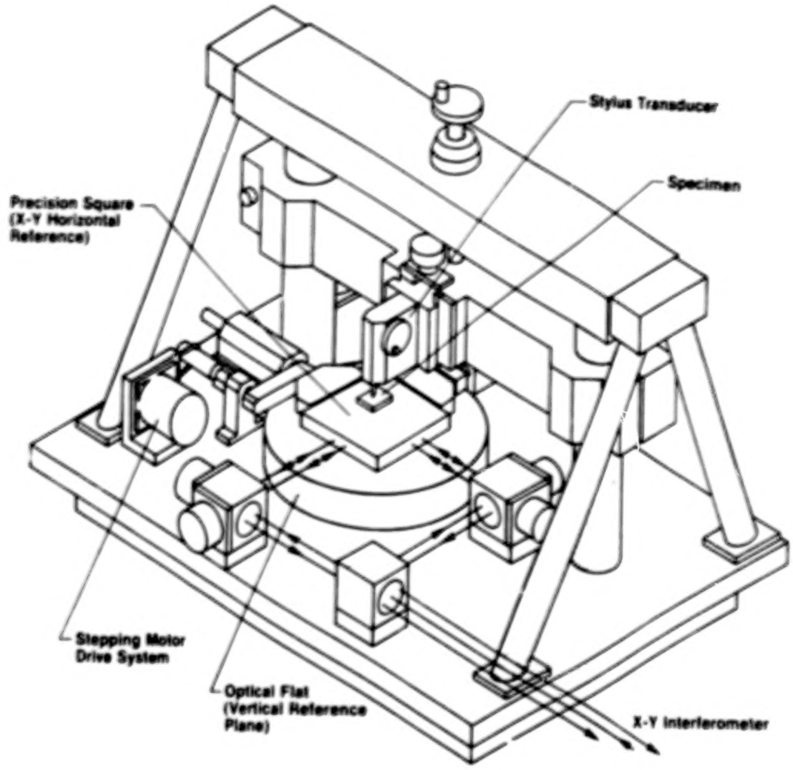
STYLUS MEASUREMENTS

- Finite Horizontal Resolution
- Potential Damage to Test Surface
- 2-D Sampling of Surface
- Slow and Difficult to Adapt to Curved Surfaces
- Detailed Quantitative Profile Output
- Combined Horizontal-Vertical Resolution Best of All Standard Techniques

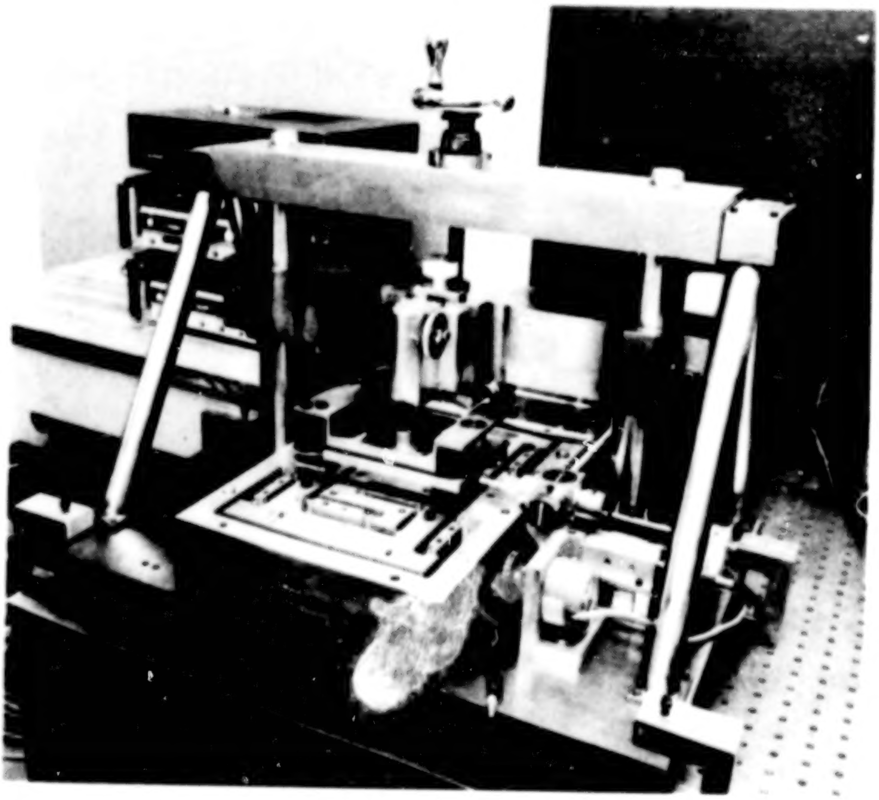
WORK TO OVERCOME LIMITATIONS

- 3-D Stylus Profilometry
- SEM Stereoscopy
- Light Scattering

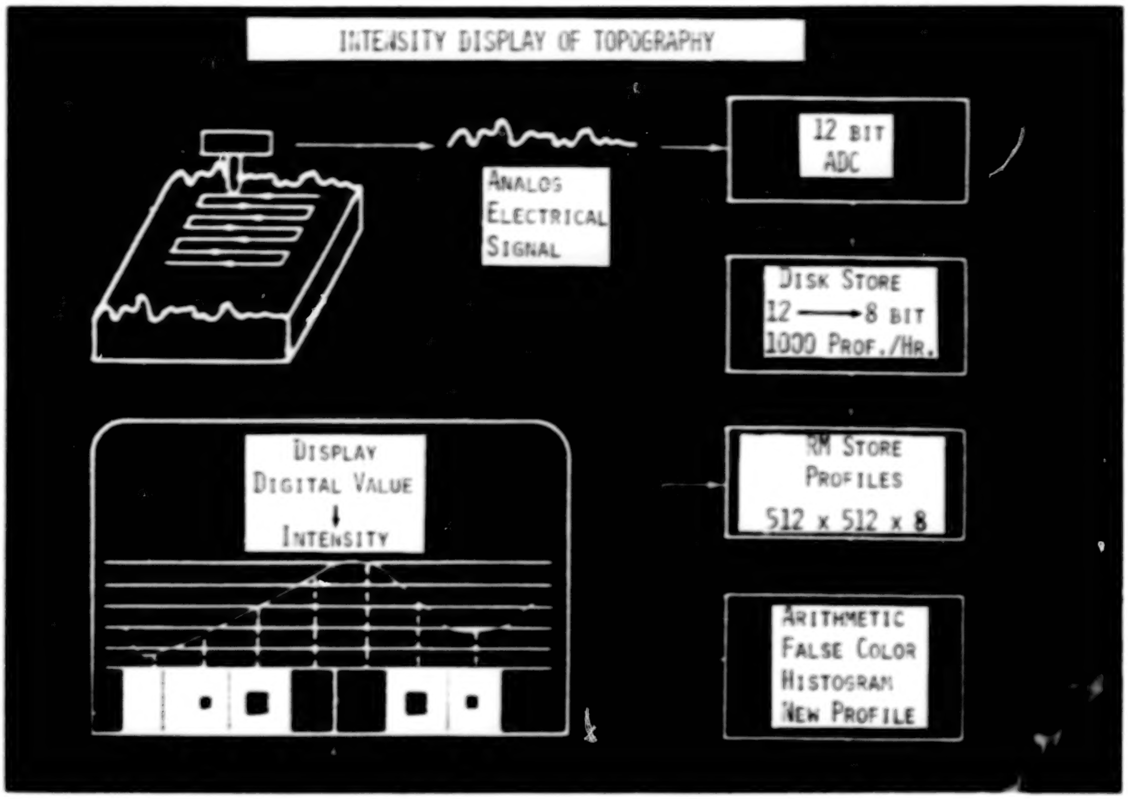
SCHEMATIC OF TOPOGRAPHY MEASURING INSTRUMENT


Stylus Transducer
Specimen
Precision Square (X-Y Horizontal Reference)
Stepping Motor Drive System
Optical Flat (Vertical Reference Plane)
X-Y Interferometer

TOPOGRAPHY MEASURING INSTRUMENT



INTENSITY DISPLAY OF TOPOGRAPHY



ANALOG
ELECTRICAL
SIGNAL

12 BIT
ADC

DISK STORE
12 ⟶ 8 BIT
1000 PROF./HR.

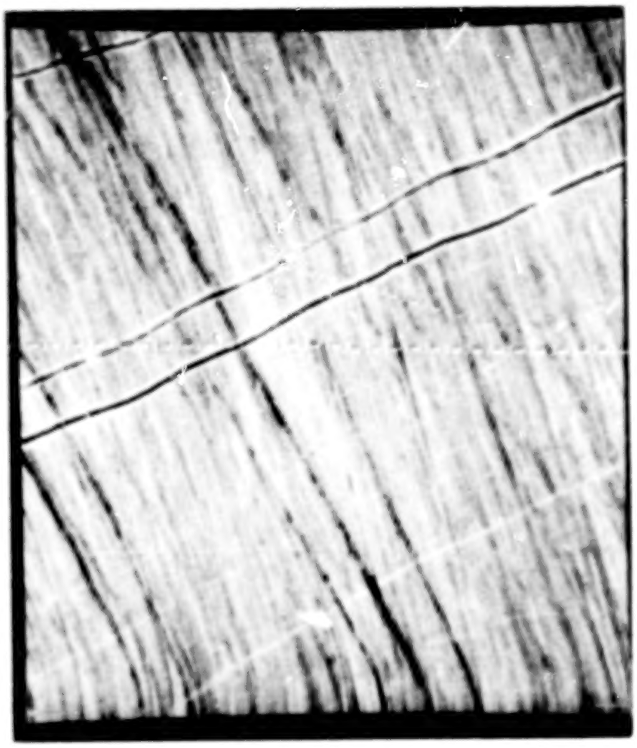
RM STORE
PROFILES
512 x 512 x 8

DISPLAY
DIGITAL VALUE
↓
INTENSITY

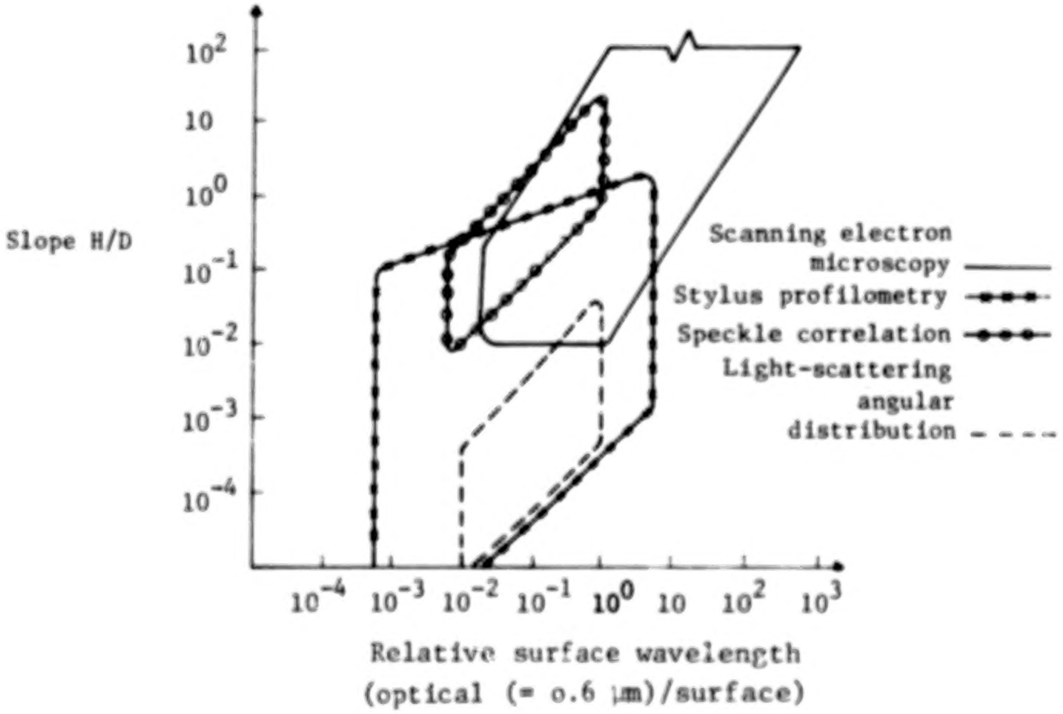
ARITHMETIC
FALSE COLOR
HISTOGRAM
NEW PROFILE

3-D STYLUS PROFILOMETRY
NASA TEST SPECIMEN 1 MM SQUARE
NBS SURFACE CHARACTERIZATION GROUP
[illegible] HEIGHT CHANGE O[illegible]

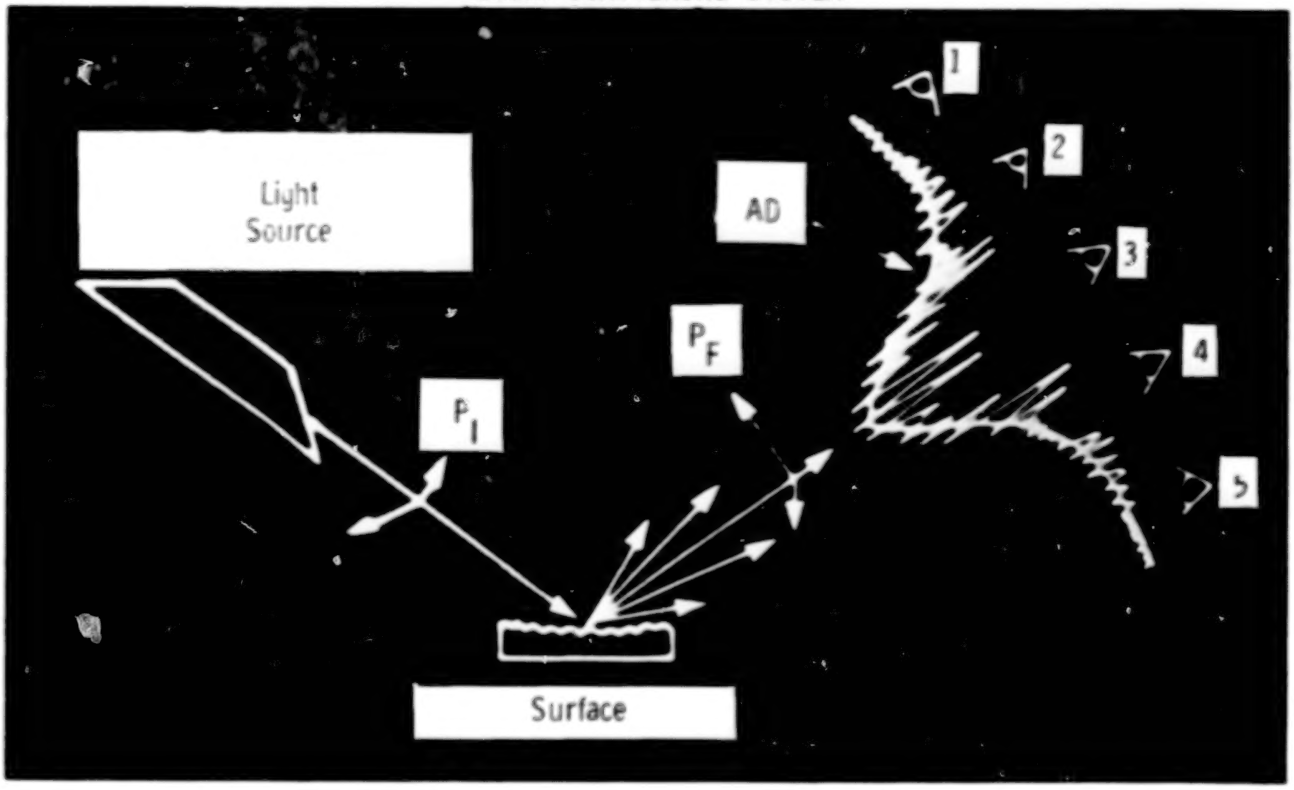
POTENTIAL STYLUS DAMAGE TO SPECIMEN



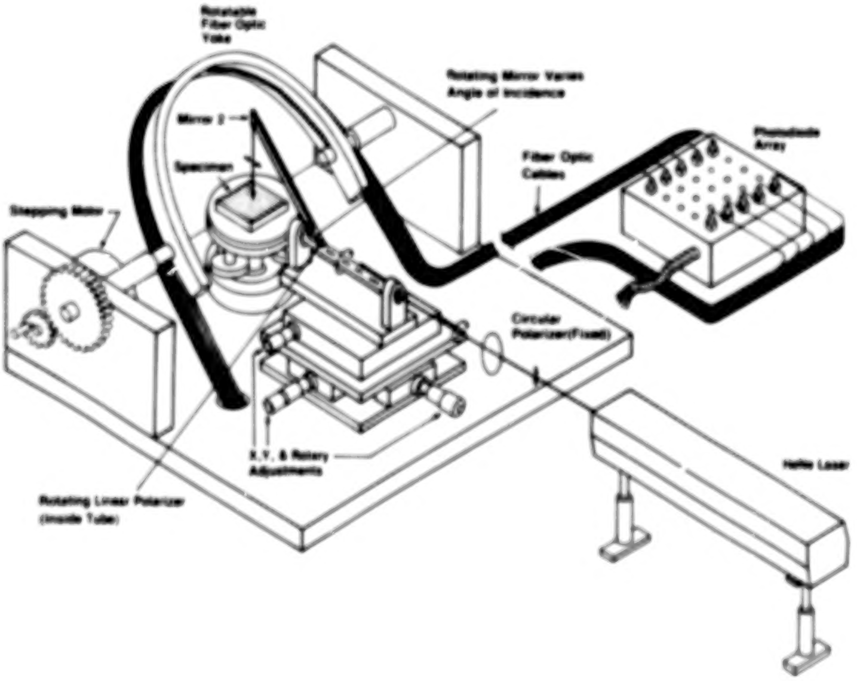
SENSITIVITY REGIONS FOR SURFACE MICROTOPOGRAPHY INSTRUMENTS



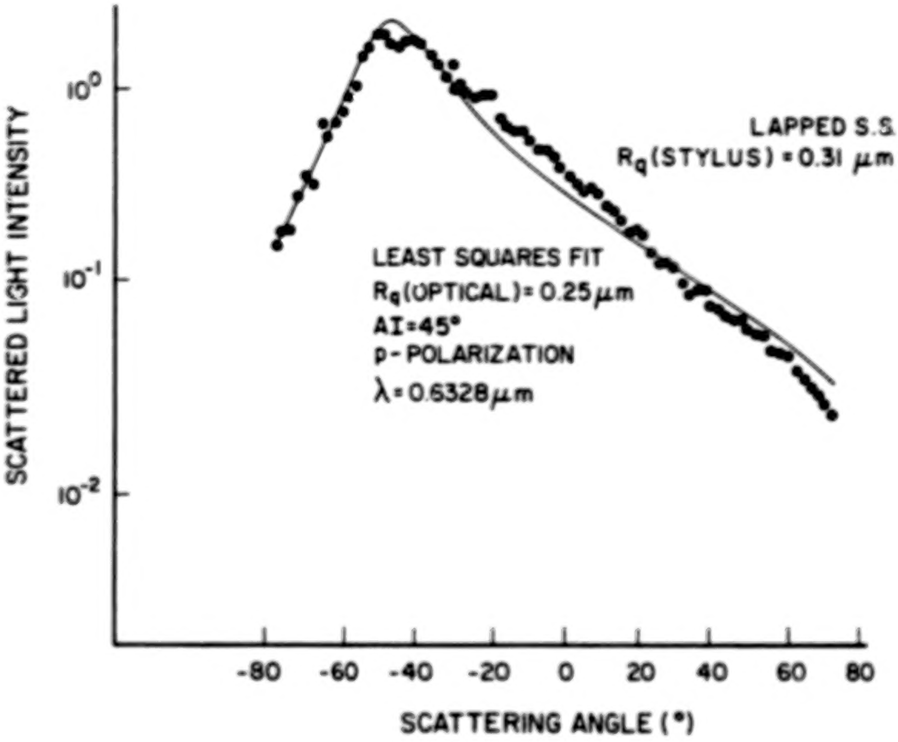
LIGHT-SCATTERING SYSTEM


1
2
AD
3
Light Source
P_F
4
P_I
5
Surface

DETECTOR ARRAY FOR LASER LIGHT ANGULAR SCATTERING

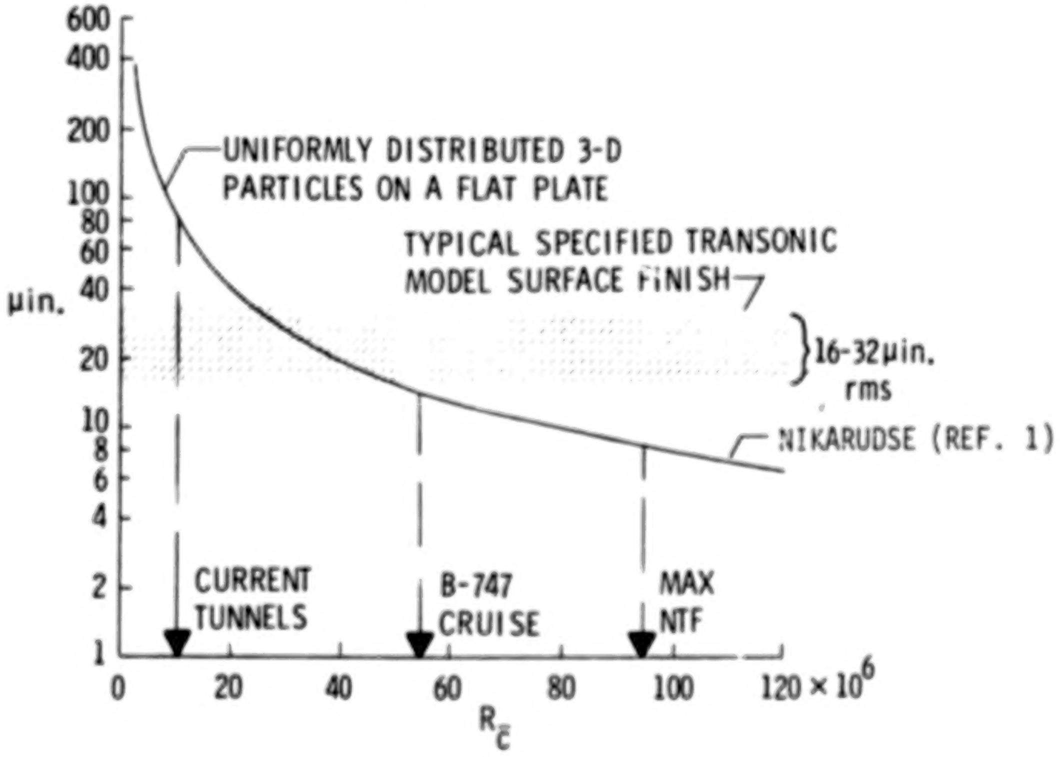

Rotatable Fiber Optic Yoke
Rotating Mirror Varies Angle of Incidence
Mirror 2
Specimen
Photodiode Array
Fiber Optic Cables
Stepping Motor
Circular Polarizer(Fixed)
X,Y, & Rotary Adjustments
HeNe Laser
Rotating Linear Polarizer (inside Tube)

PRELIMINARY RESULTS - LIGHT SCATTERING
THEORY VERSUS EXPERIMENT

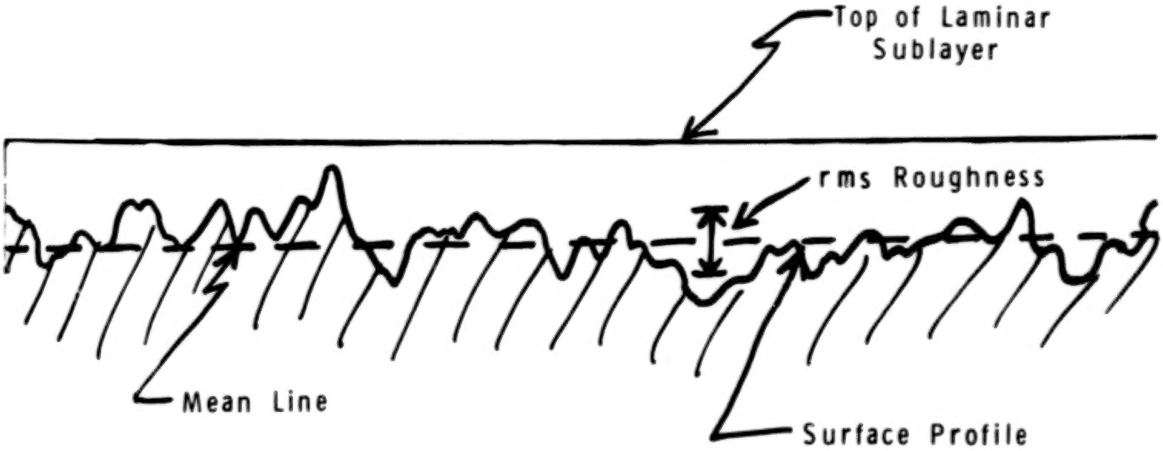


ACCEPTABLE ROUGHNESS FOR TYPICAL NTF MODEL

$\bar{c}$ = 0.20 m

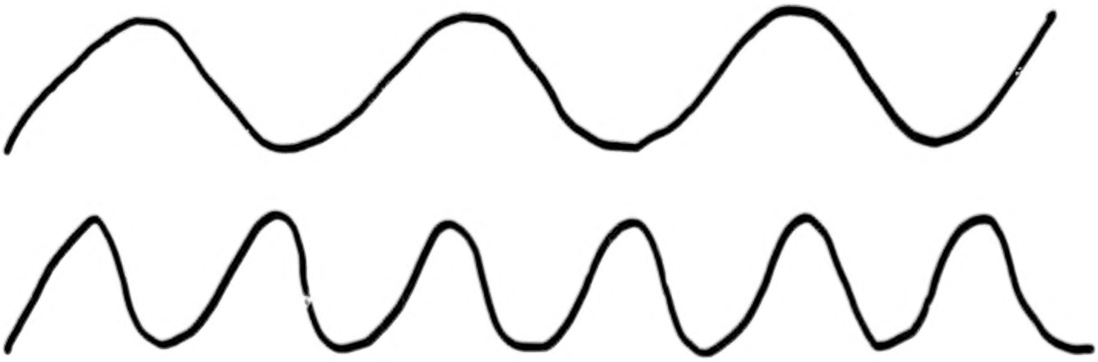


- What Is Admissible Height ?
  - Maximum Peak to Mean Line
  - RMS Height
- Is Admissible Height a Function of Peak Density ?


Top of Laminar Sublayer
rms Roughness
Mean Line
Surface Profile

PARAMETER NEEDS

- Height Measure
- Wavelength Measure



Same rms

STRAIN GAGE BALANCES AND BUFFET GAGES

Alice T. Ferris
NASA Langley Research Center
Hampton, Virginia

One-piece strain gage force balances have been developed at NASA Langley Research Center for use in the National Transonic Facility (NTF). This was accomplished by studying the effects of the cryogenic environment on materials, strain gages, cements, solders, and moisture proofing agents, and selecting those that minimized strain gage output changes due to temperature. In addition, because of the higher loads that may be imposed by the NTF, these balances are designed to carry a larger load for a given diameter than conventional balances. Full cryogenic calibrations have been accomplished, and wind tunnel results that were obtained from the Langley 0.3-Meter Transonic Cryogenic Tunnel were used to verify laboratory test results.

CRYOGENIC FORCE INSTRUMENTATION

NEW REQUIREMENTS

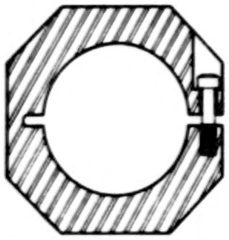
- WIDER OPERATING TEMPERATURE RANGE
- INCREASED LOAD-TO-DIAMETER RATIO (NTF)

BALANCE MATERIALS
NTF

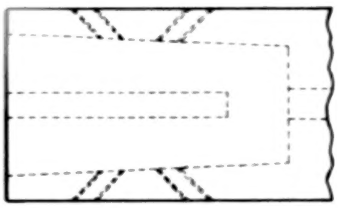
MATERIAL	TENSILE STRENGTH (KSI)		IMPACT STRENGTH CHARPY-V (FT-LBS)	
	YIELD	ULTIMATE	ROOM	77K
MARAGING 200	212	216	29	17
MARAGING 250	260	270	15	11
		CONVENTIONAL		
17-4 PH	175	190	7	2
MARAGING 300	291	299	12	7

NTF-101 BALANCE

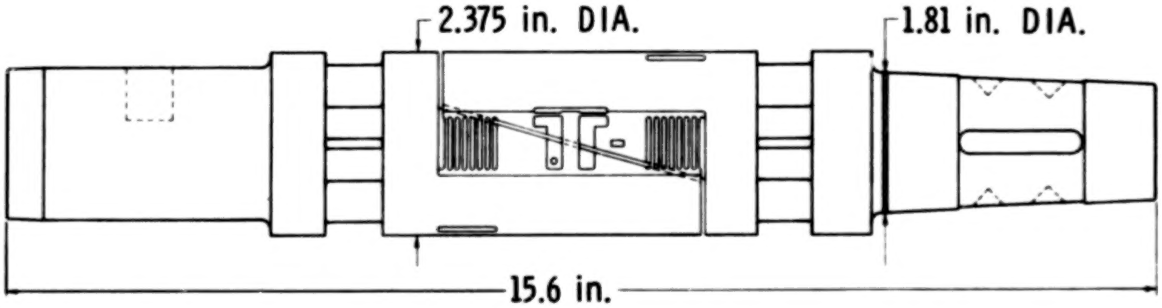
6500 lb NORMAL



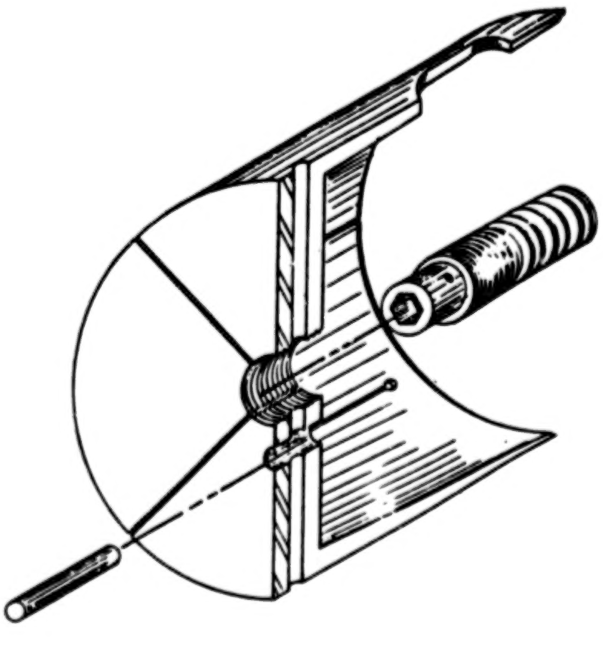
TYPICAL MODEL ADAPTOR FOR NTF-101 BALANCE



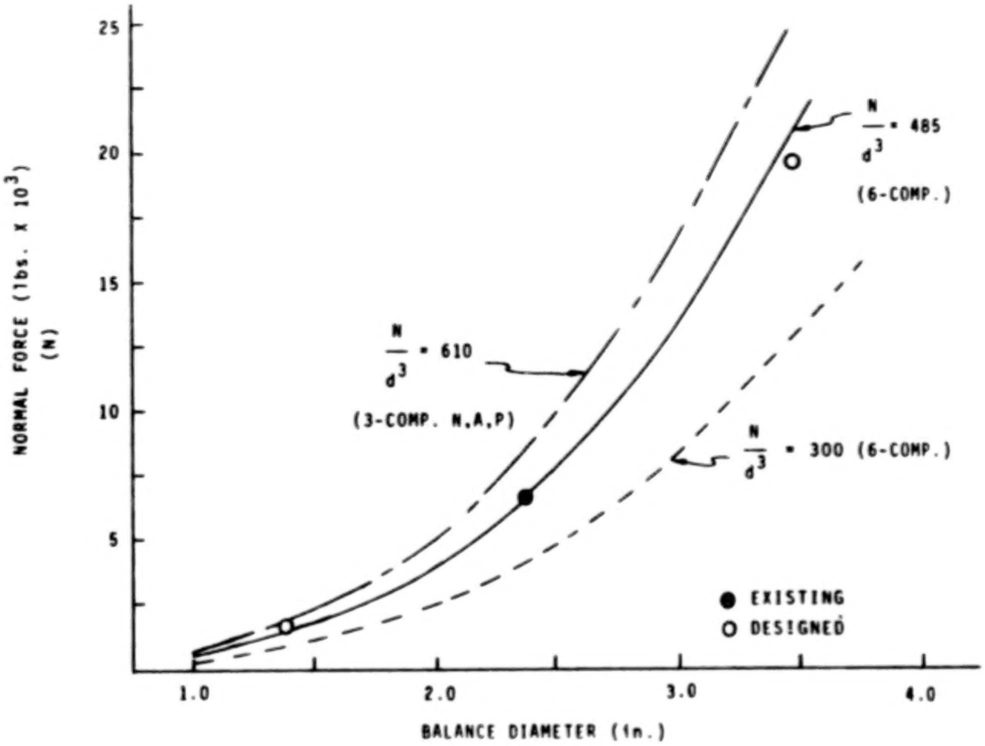
TYPICAL STING ATTACHMENT FOR NTF-101 BALANCE


2.375 in. DIA.
1.81 in. DIA.
15.6 in.

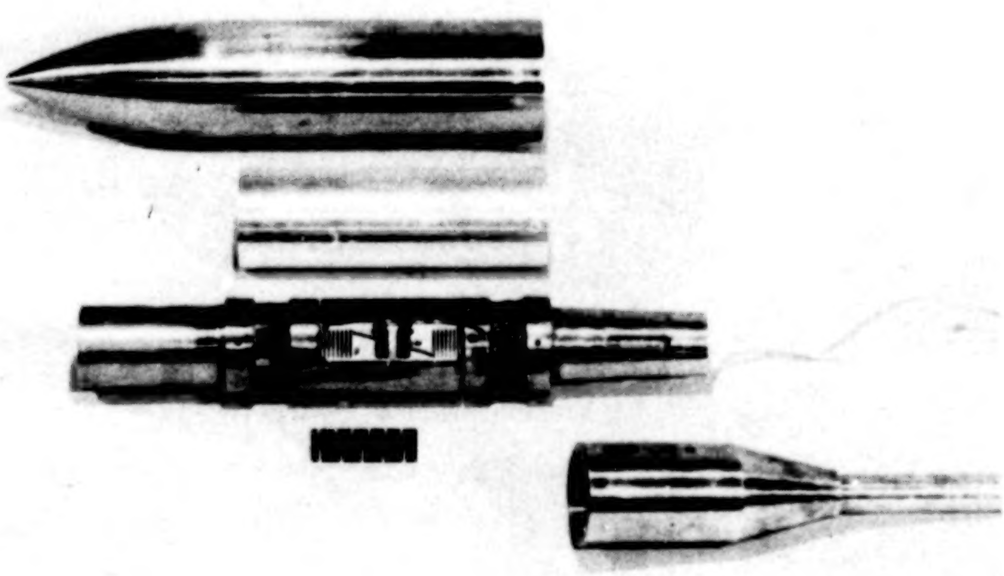
MODEL END EXPANDER



BALANCE LOAD vs DIAMETER



NTF-101 BALANCE AND ASSOCIATED 0.3-m TCT HARDWARE



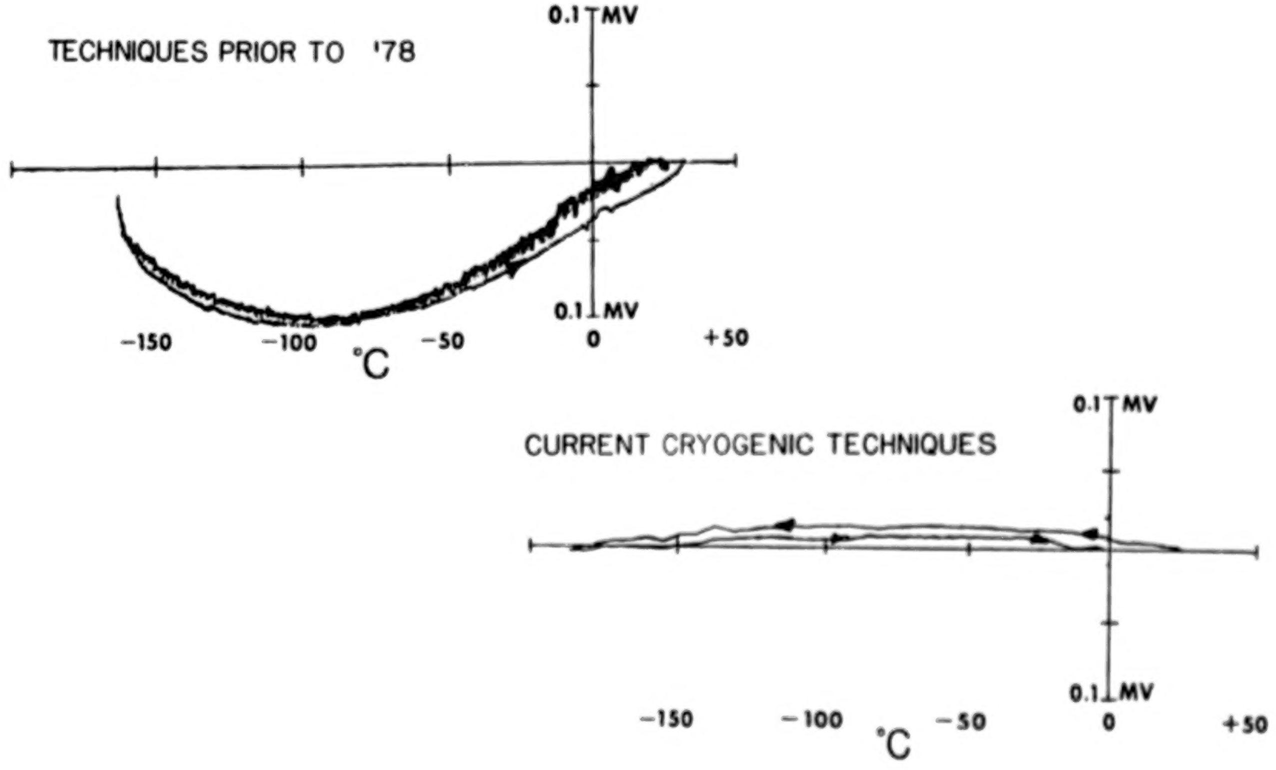
BEST DOCUMENT AVAILABLE

GAGE MATCHING PROCEDURE

- TEMPORARY BONDING
- DATA ACQUISITION AND MATCHING
- DISBONDING AND INSTALLATION

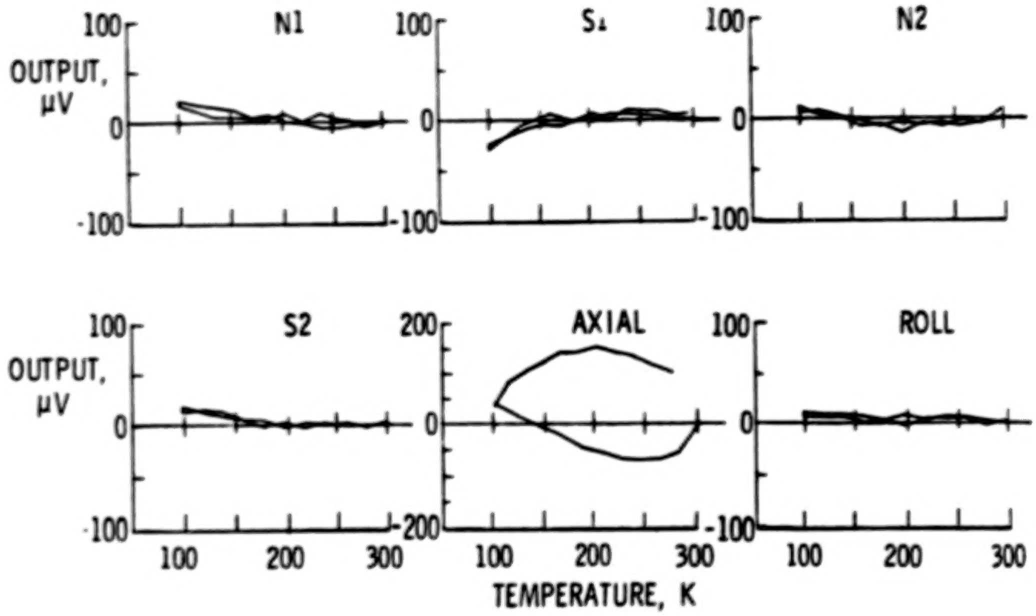
IMPROVED STRAIN GAGING TECHNIQUES

THERMAL RESPONSE OF A FOUR-ARM BRIDGE

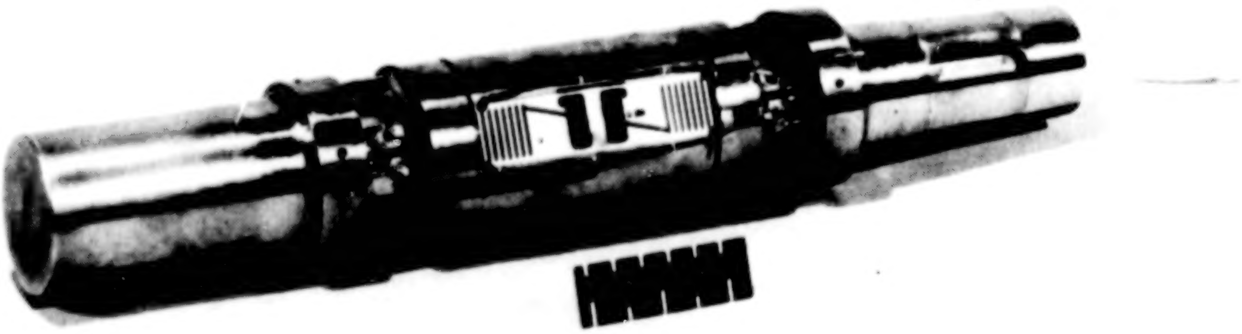


NTF-101 BALANCE

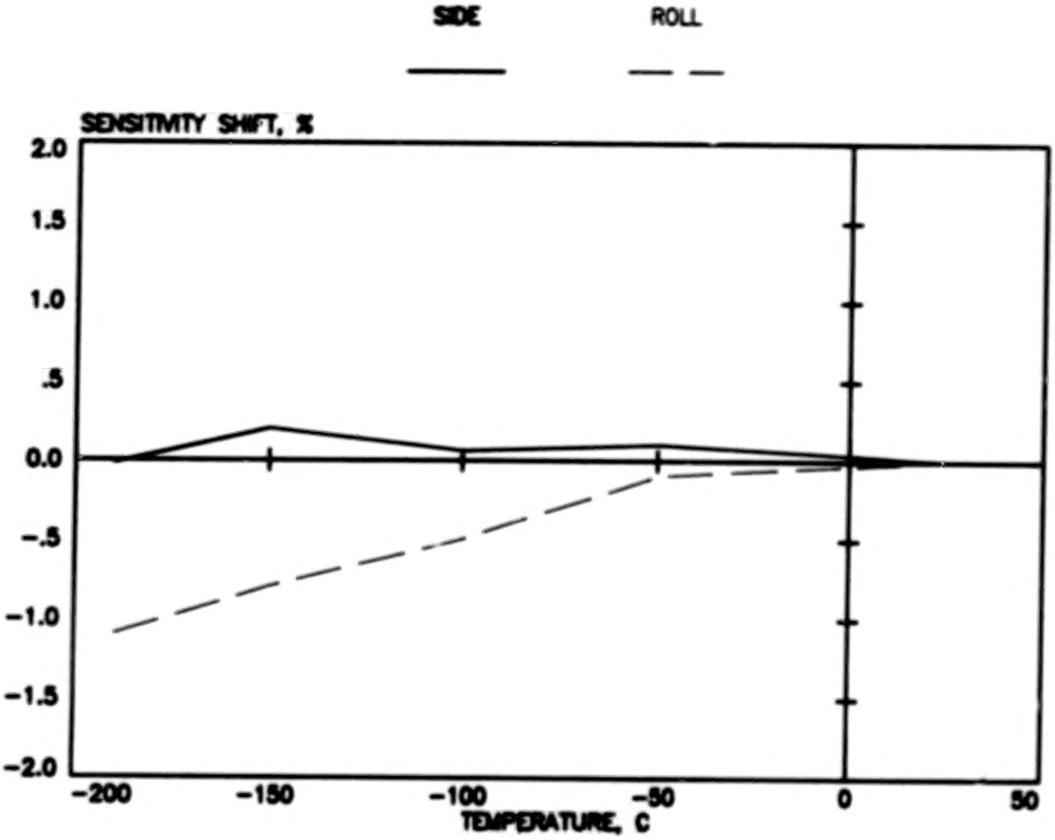
OUTPUT VERSUS TEMPERATURE



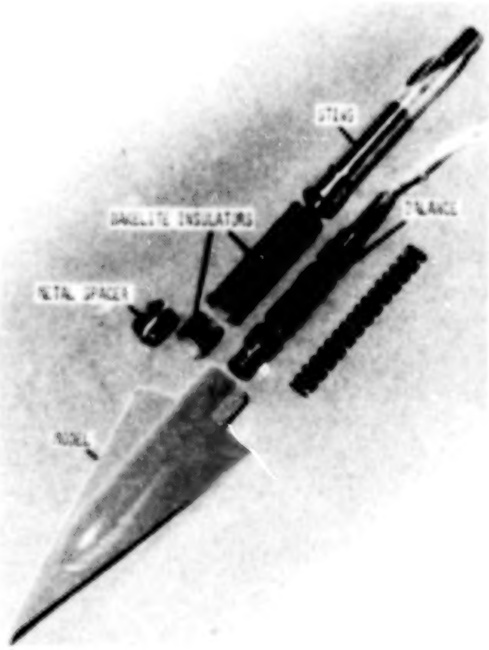
NTF-101 BALANCE

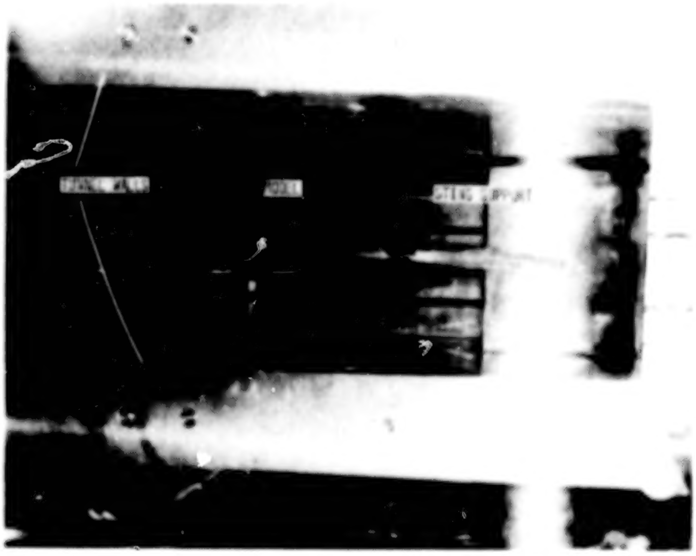


SENSITIVITY SHIFT VS TEMPERATURE

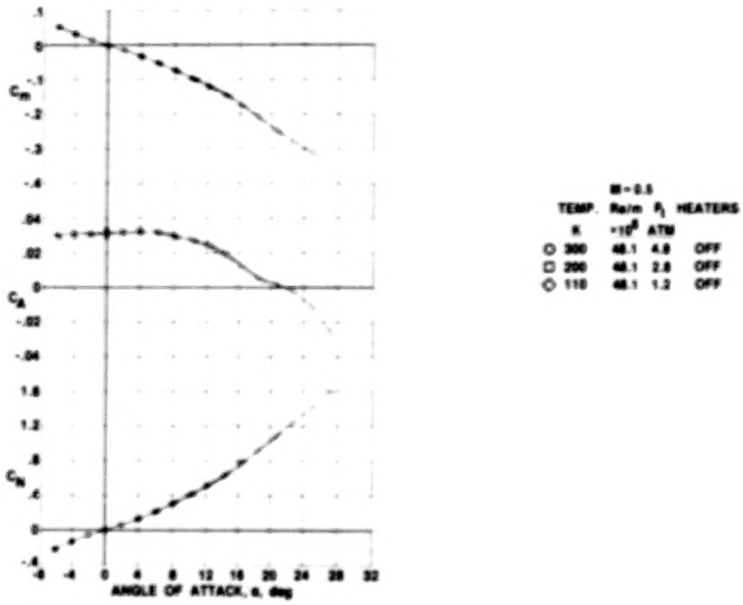


0.3-m TCT EVALUATION TESTS


STING
BALANCE
BAKELITE INSULATORS
METAL SPACER
MODEL


TUNNEL WALL
MODEL
STING SUPPORT

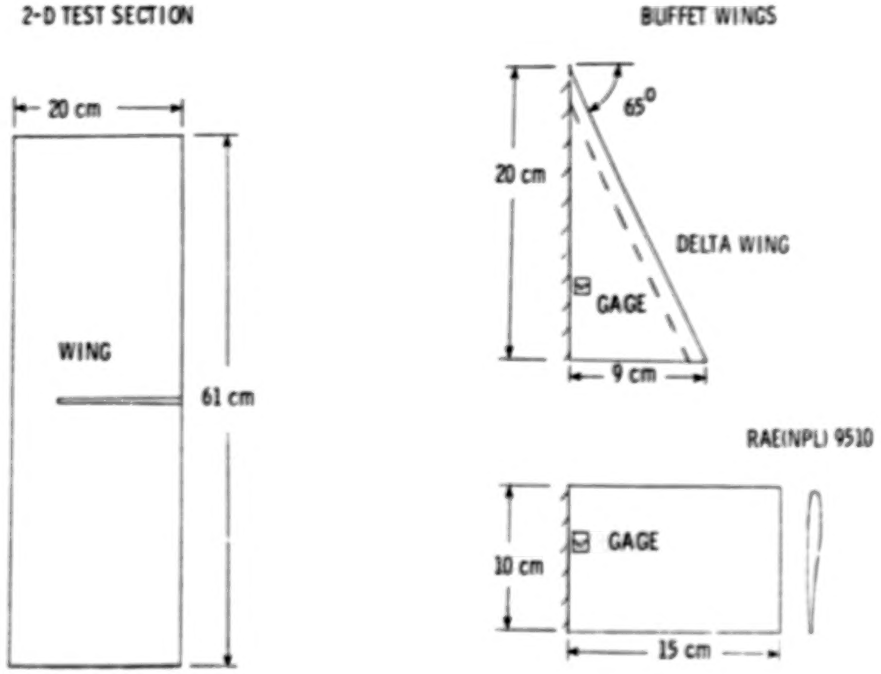
0.3m CRYOGENIC WIND TUNNEL TEST RESULTS



NTF BALANCES

BALANCE DESIGNATION	SIZE DIAM IN	COMPONENT N LBS	 A LBS	 m IN-LBS	 ℓ IN-LBS	 n IN-LBS	 Y LBS
NTF101-A	2-3/8	6,500	700	13,000	9,000	6,500	4,000
NTF101-B	2-3/8	6,500	700	13,000	9,000	6,500	4,000
NTF102	2	3,000	600	6,000	600	600	300
NTF103	2	1,500	300	3,000	300	300	150
NTF104	2	3,400	300	10,000	5,000	5,000	1,000
NTF105	2	2,000	175	6,000	3,000	3,000	700
NTF106	2	3,700	550	11,500	2,000	2,000	500
NTF107	3/4	160	50	400	100	200	80
NTF108	1-1/2	1,600	125	3,000	1,500	1,500	500

BUFFET WINGS FOR 0.3m TRANSONIC CRYOGENIC TUNNEL


2-D TEST SECTION
20 cm
WING
61 cm
BUFFET WINGS
65°
20 cm
DELTA WING
GAGE
9 cm
RAE(NPL) 9510
GAGE
10 cm
15 cm

BUFFET MODELS TESTED IN 0.3-m TCT

CONCLUSIONS

- MATERIALS HAVE BEEN SELECTED FOR CRYOGENIC USE
- GAGING TECHNIQUES HAVE BEEN DEVELOPED TO MINIMIZE TEMPERATURE INDUCED OUTPUT
- MATERIALS AND TECHNIQUES HAVE BEEN VERIFIED IN CRYOGENIC WIND TUNNEL TESTS

MODEL DEFORMATION SYSTEM

Harlan K. Holmes
NASA Langley Research Center
Hampton, Virginia

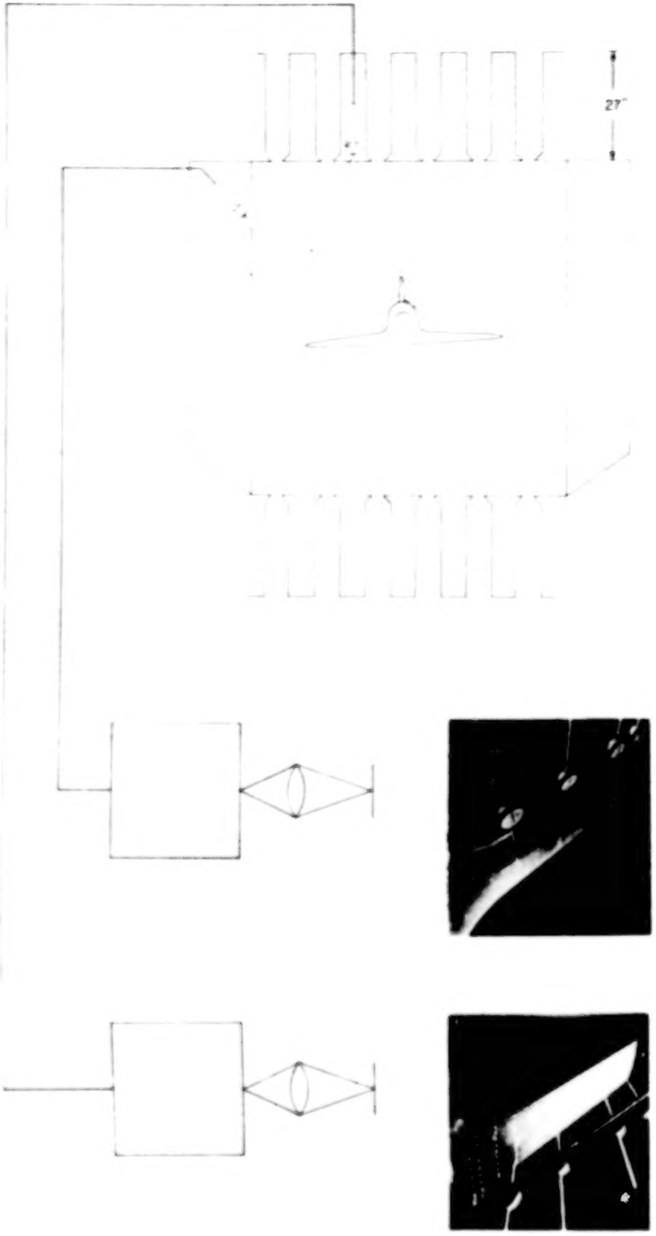
The high model loads to be encountered in the National Transonic Facility (NTF) will cause large model deflections, thus creating a new measurement requirement, that of measuring model deformation. Our goal is to be able to measure peak deflections of up to 3 in. with accuracies to within 0.0025 in. over an area 1 m square as the model pitches through an included angle of 30°. Stereophotogrammetric techniques are being implemented, with the initial system being an extension of standard techniques. A second system, which will be all electronic, is under development. Both techniques will require targets to be strategically placed on the model. Active targets are being developed for location in the model in order to maximize the signal-to-noise ratio and to approximate a point source. Image-processing techniques and stereophotogrammetric data reduction programs are being implemented to perform the data reduction tasks.

SPECIFIC TECHNICAL REQUIREMENTS

- VIEWING AREA - 36 IN. SQUARE
- MODEL PITCH - 11 TO +19 DEGREES
- MEASUREMENT TIME - < 2 SECONDS
- NUMBER OF POINTS - UP TO 50
- MAXIMUM DEFLECTION - 3 INCHES
- ACCURACY DESIRED - ± 0.0025 INCHES
- ENVIRONMENT
    - TEMPERATURE - 140 TO 610°R
    - PRESSURE - 130 PSIA MAX
    - SOUND PRESSURE - 150dB SPL

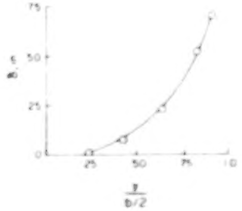
MODEL DEFORMATION MEASUREMENT FOR NTF

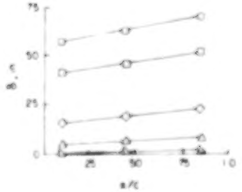
- EXTENSION OF STANDARD TECHNIQUE
- REAL-TIME MONITORING OF DATA
- DOES NOT REQUIRE TUNNEL ENTRY
- UPGRADABLE (DIGITAL IMAGE PROCESSING)



COMPARATOR

DATA REDUCTION





SCANNING STEREO PHOTOGRAMMETRY

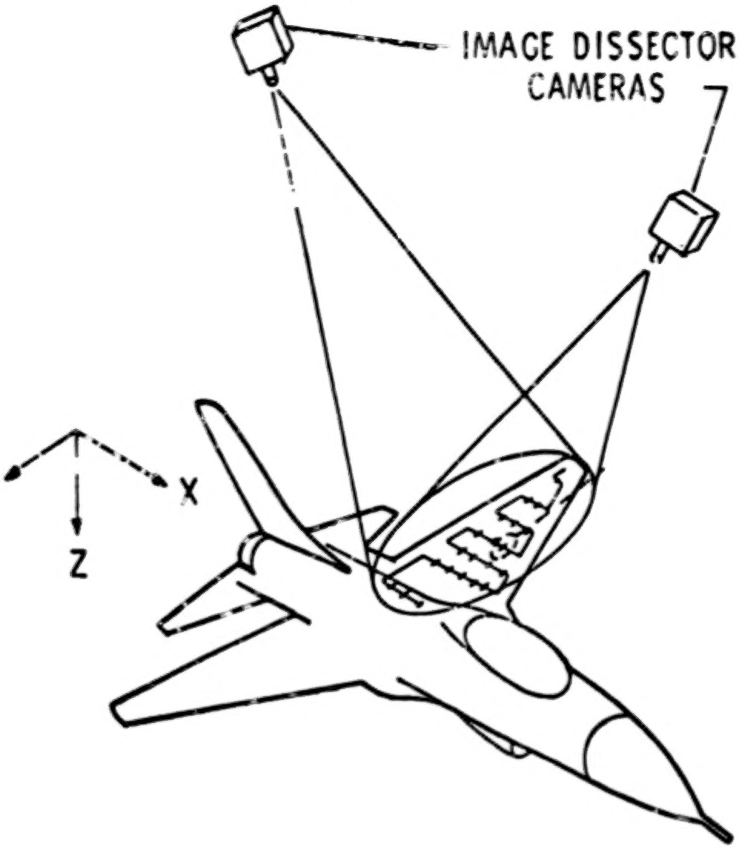
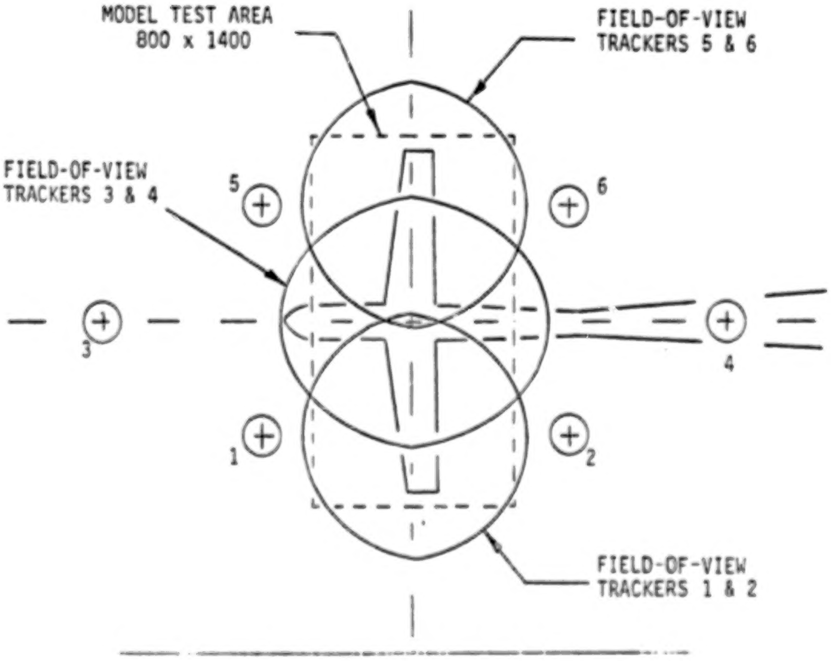


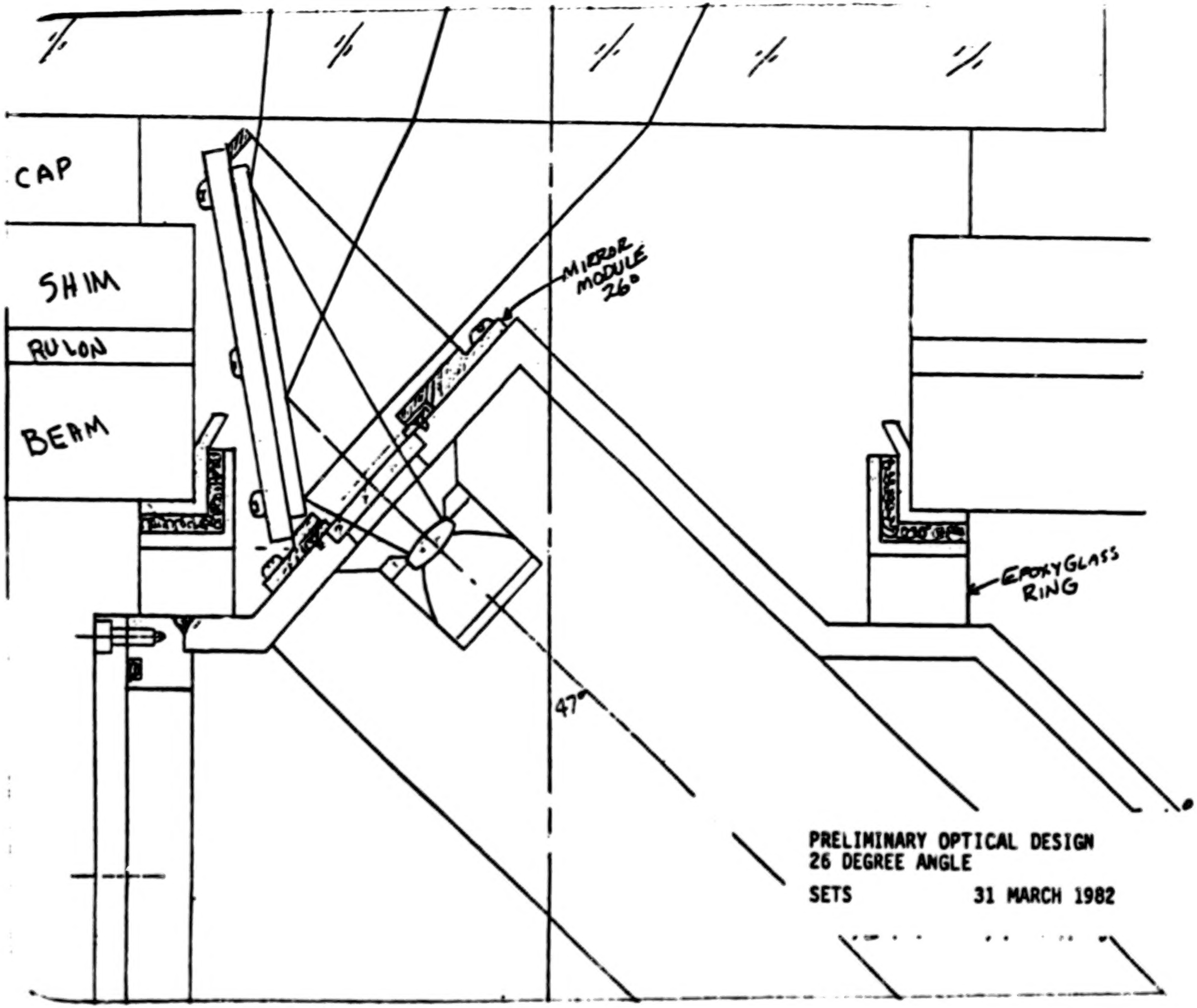
IMAGE DISSECTOR CAMERAS
X
Z

STEREO ELECTROOPTIC TRACKING SYSTEM (SETS) FIELD OF VIEW


MODEL TEST AREA 800 x 1400
FIELD-OF-VIEW TRACKERS 5 & 6
FIELD-OF-VIEW TRACKERS 3 & 4
5
6
3
4
1
2
FIELD-OF-VIEW TRACKERS 1 & 2

NOTE: FIELDS OF VIEW ARE IN A PLANE THROUGH THE TUNNEL CENTER LINE (Z=0)

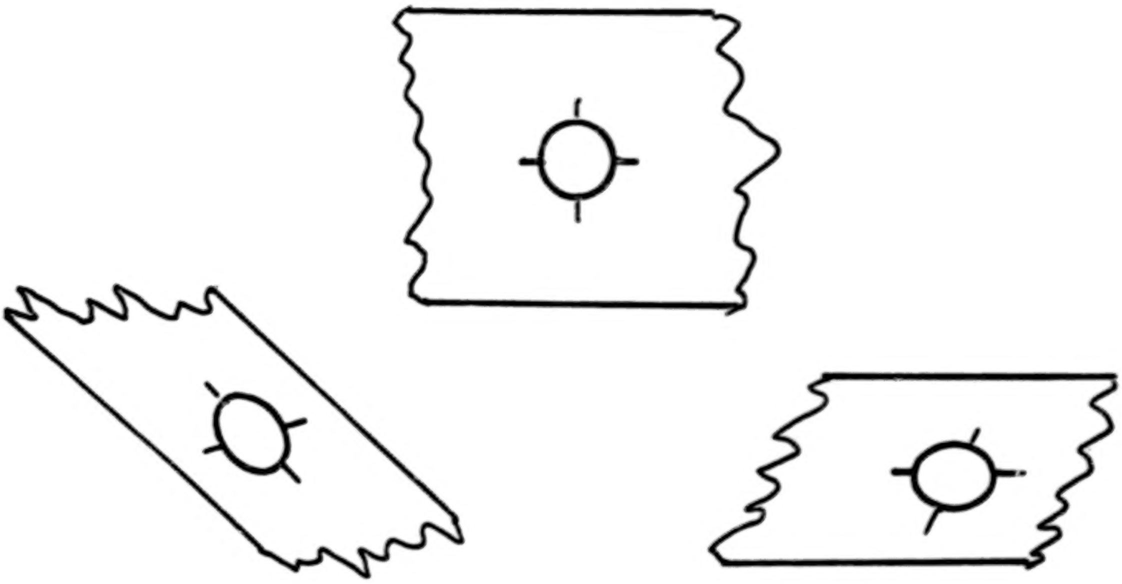
SETS PRELIMINARY OPTICAL DESIGN (26° angle)


CAP
SHIM
RULON
BEAM
MIRROR MODULE 26°
EPOXYGLASS RING
47°

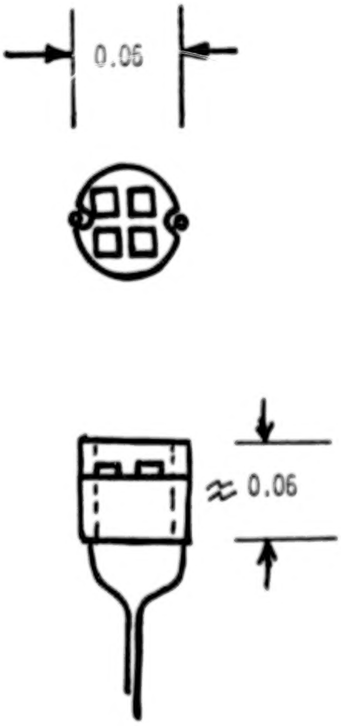
PRELIMINARY OPTICAL DESIGN
26 DEGREE ANGLE
SETS 31 MARCH 1982

BEST DOCUMENT AVAILABLE

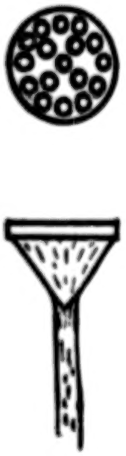
TARGET ORIENTATION



ACTIVE TARGET CONCEPTS



MULTIPLE LED



MULTIPLE FIBER

NTF MODEL PRESSURE MEASUREMENTS

Fredrick A. Kern
NASA Langley Research Center
Hampton, Virginia

Pressure measurements on the NTF models will be made using electronically scanned pressure instrumentation. The system consists of pressure modules, a pressure calibration standard, and a system controller. The pressure modules, which must be operated above -18°C, will be housed in model-integrated designed thermally controlled containers. The Pathfinder I 192-channel pressure package is described. Recent and planned developments to reduce the pressure module's volume per channel ratio are discussed, including the 48-channel module and a proposed 32-channel module that would be 2.54 by 2.54 by 8.13 cm. Pressure transducers capable of operating at cryogenic temperatures for dynamic and static pressure measurements are discussed.

PRESSURE INSTRUMENTATION

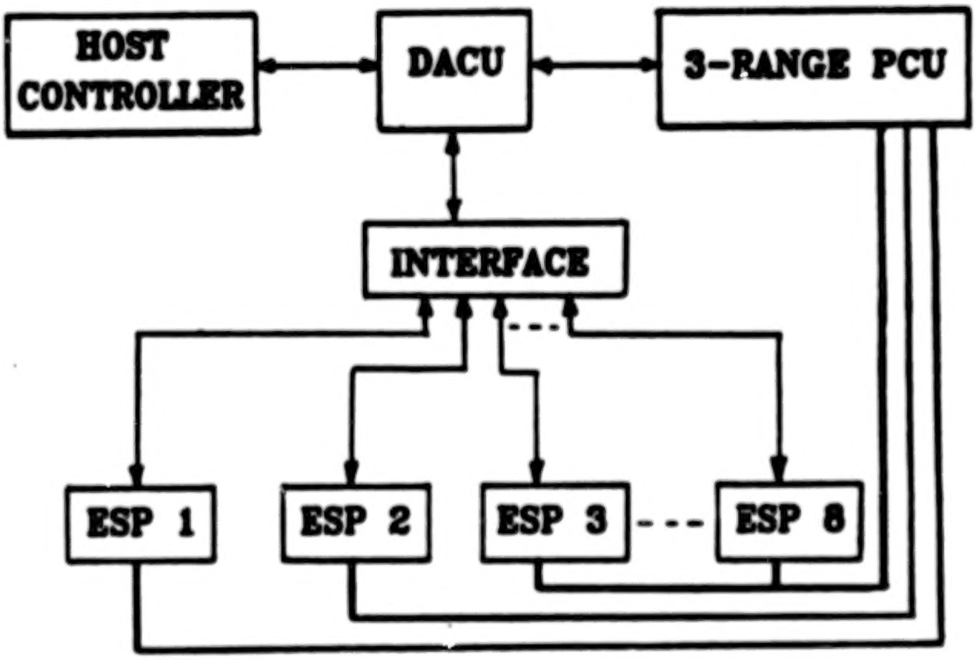
STEADY-STATE MEASUREMENTS

- **ESP SYSTEMS**
- **PIEZORESISTIVE TRANSDUCERS**

DYNAMIC MEASUREMENTS

- **PIEZORESISTIVE TRANSDUCERS**
- **PIEZOELECTRIC TRANSDUCERS**

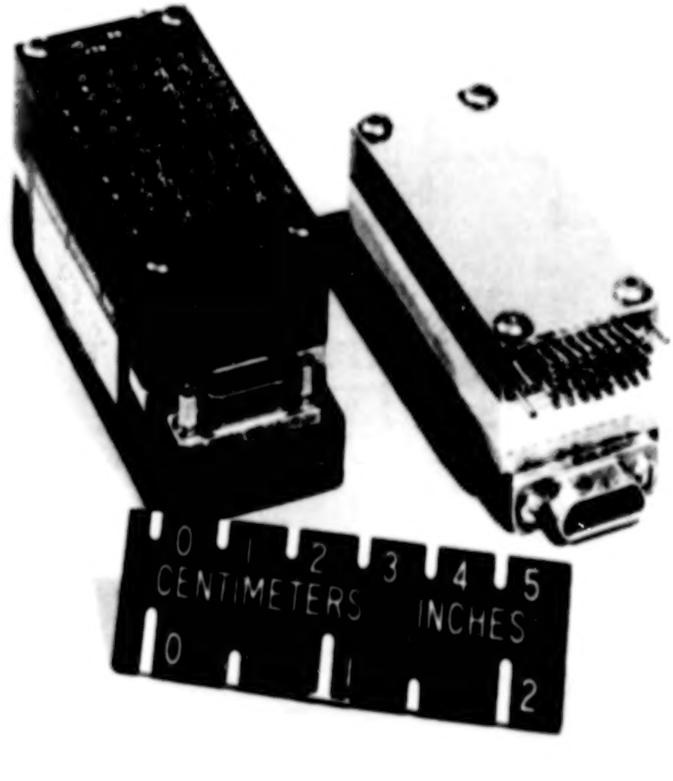
ESP MEASUREMENT SYSTEM


HOST CONTROLLER
DACU
3-RANGE PCU
INTERFACE
ESP 1
ESP 2
ESP 3
ESP 8

32-CHANNEL PRESSURE MODULE

RANGE	**5 TO 100 PSID**	
UNCERTAINTY	**0.15% FULL RANGE**	
TEMP. RANGE	**-17 TO 80 C**	
THERMAL SENSITIVITY	**0.09% / C**	
THERMAL ZERO	**0.09% FULL RANGE / C**	
SIZE	**6.4 X 2.54 X 3.7 CM**	**6.4 X 2.54 X 4.57 CM**
VOLUME/CHANNEL	**1.88 CC**	**2.32 CC**

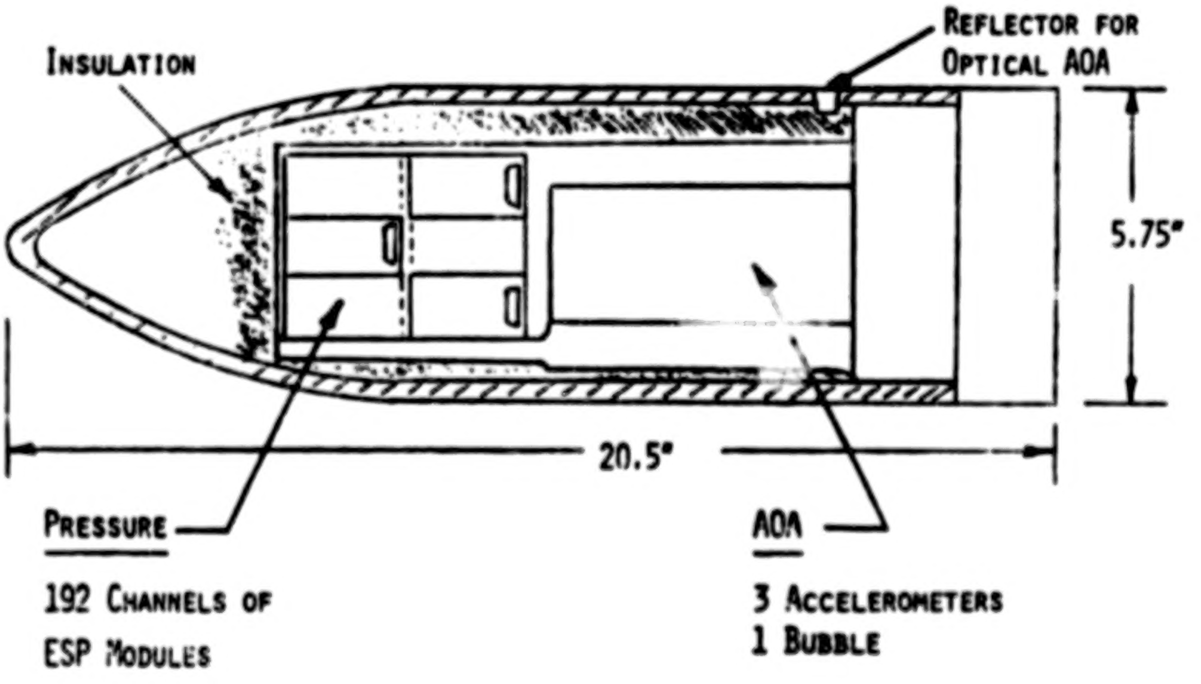
ESP (ELECTRONICALLY SCANNED PRESSURE) MODULES


0
1
2
3
4
5
CENTIMETERS
INCHES
0
1
2

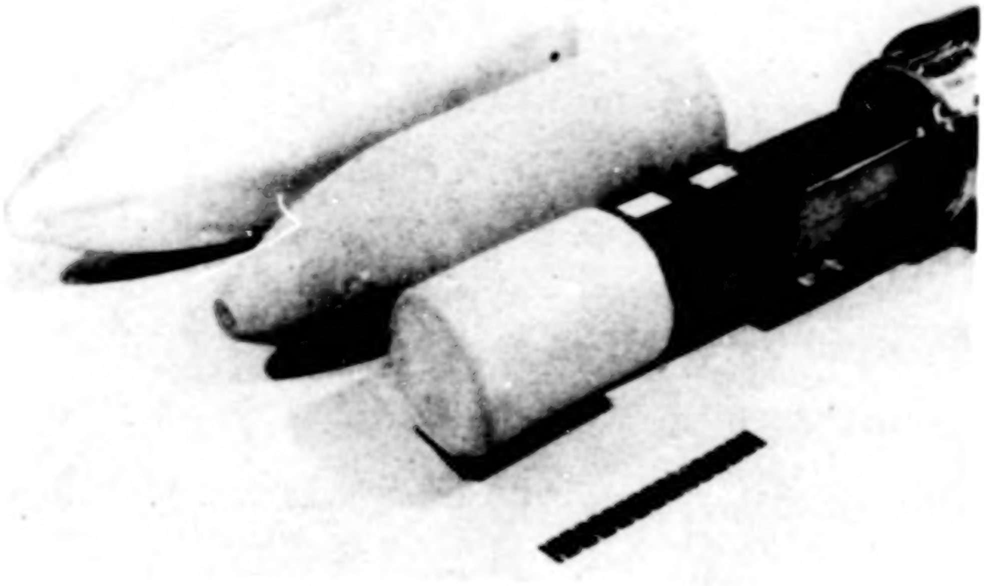
NEW PRESSURE MODULES

RANGE	**5 TO 100 PSID**	
UNCERTAINTY	**0.15% FULL RANGE**	
TEMP. RANGE	**-17 TO 80 C**	
THERMAL SENSITIVITY	**0.09% / C**	**0.05% / C**
THERMAL ZERO	**0.09% FR / C**	**0.05% FR / C**
SIZE	**6.83 X 2.84 X 3.66 CM**	**8.13 X 2.54 X 2.54 CM**
VOLUME/CHANNEL	**1.48 CC**	**1.64 CC**

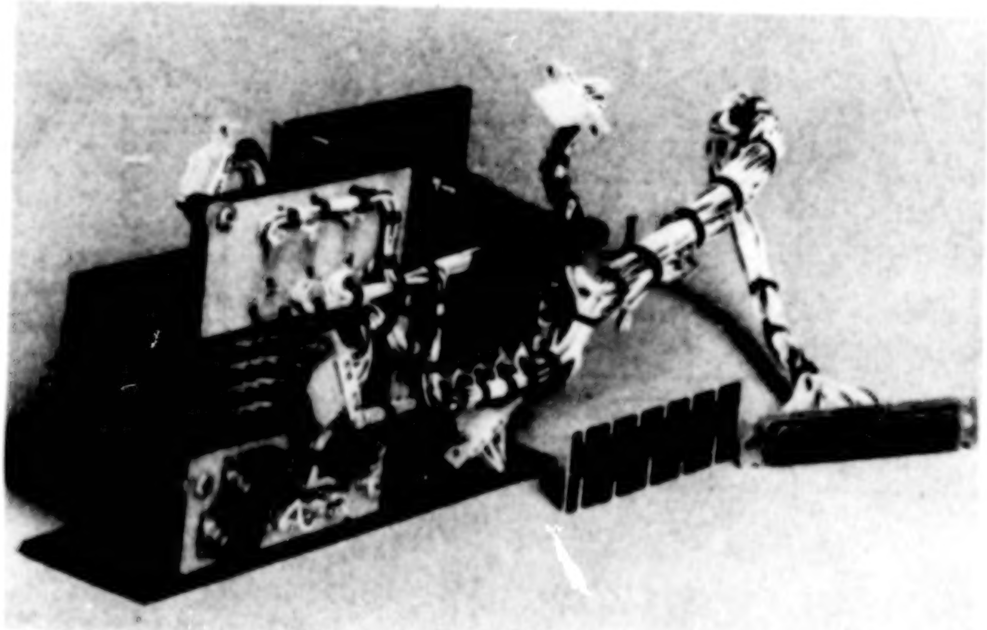
SCHEMATIC OF PATHFINDER I INSTRUMENTATION


INSULATION
REFLECTOR FOR
OPTICAL AOA
5.75"
20.5"
PRESSURE
192 CHANNELS OF
ESP MODULES
AOA
3 ACCELEROMETERS
1 BUBBLE

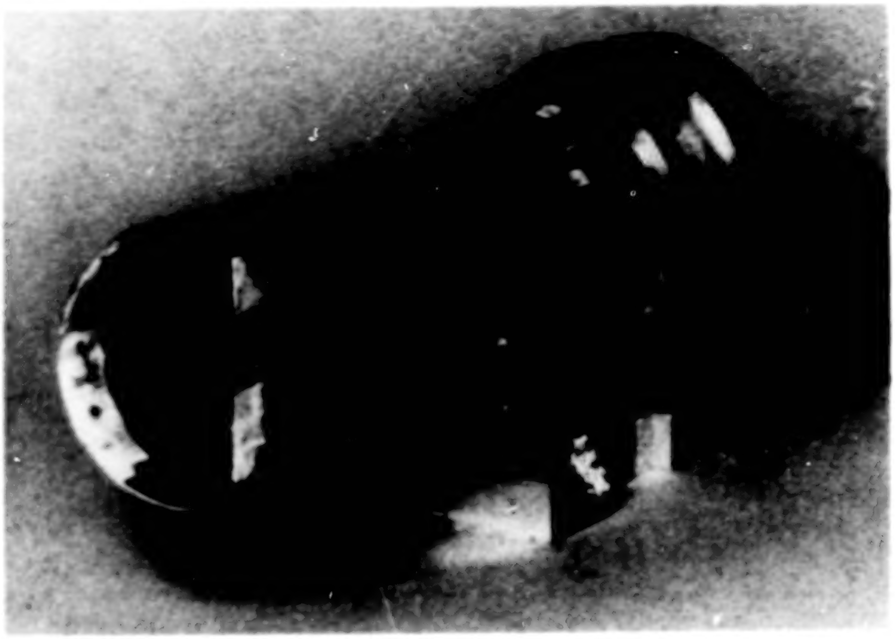
PATHFINDER I INSTRUMENTATION



PATHFINDER I ESP INSTALLATION

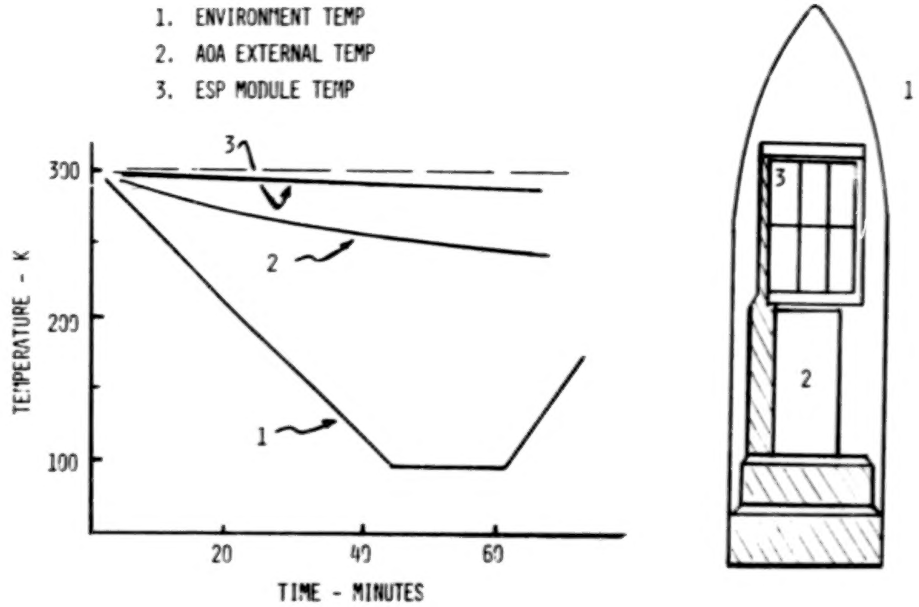


PATHFINDER I ESP HEATING SYSTEM

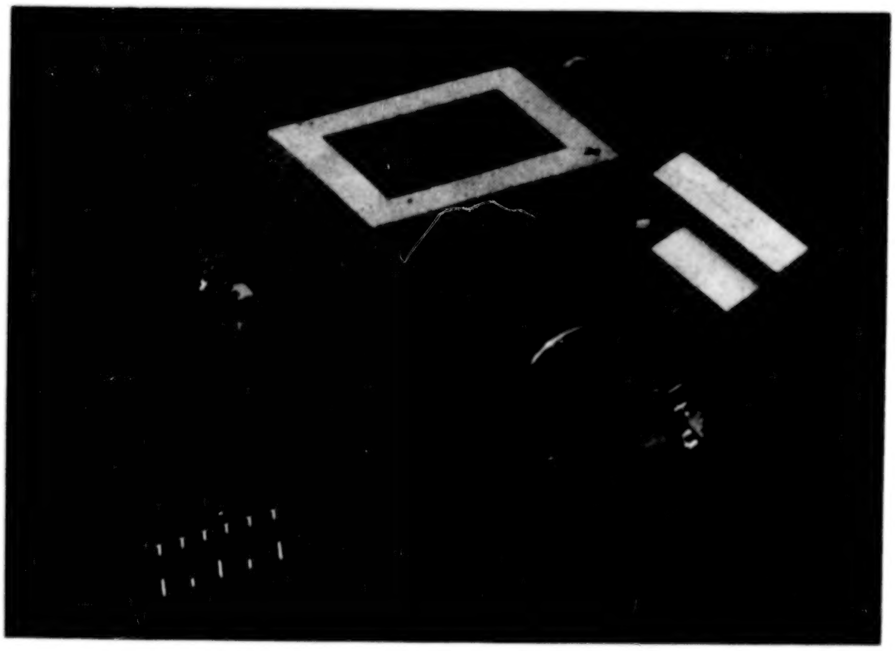


PATHFINDER I ESP PRESSURE AND ELECTRICAL CONNECTORS

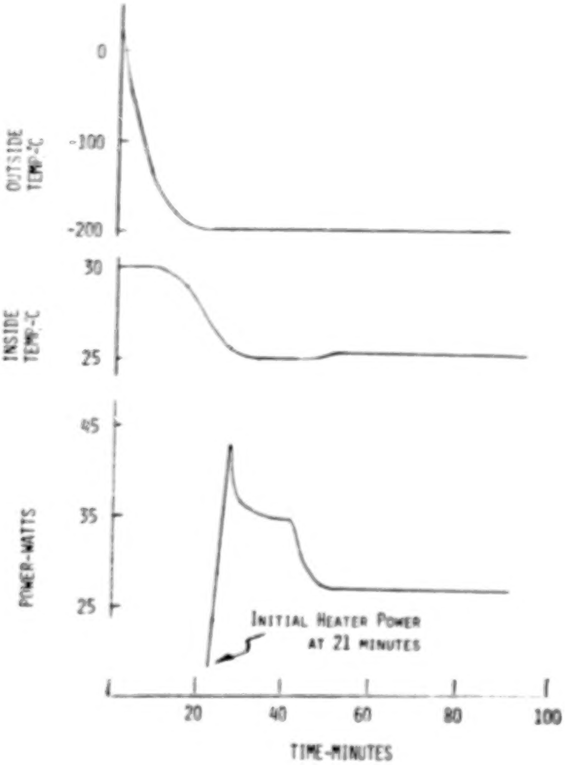
PATHFINDER THERMAL TEST



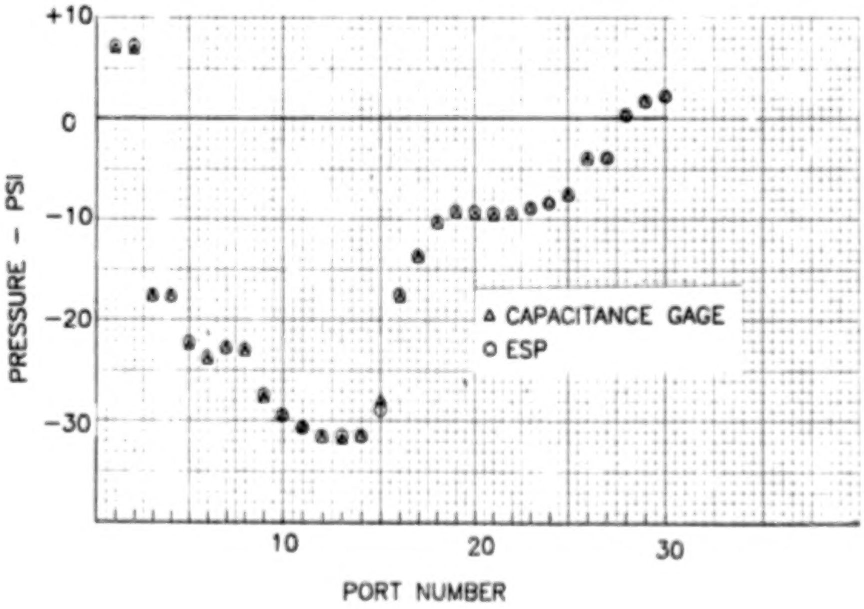
ESP PACKAGE FOR 0.3-m TCT TEST



HEATING SYSTEM PERFORMANCE DURING 0.3-M TCT TEST

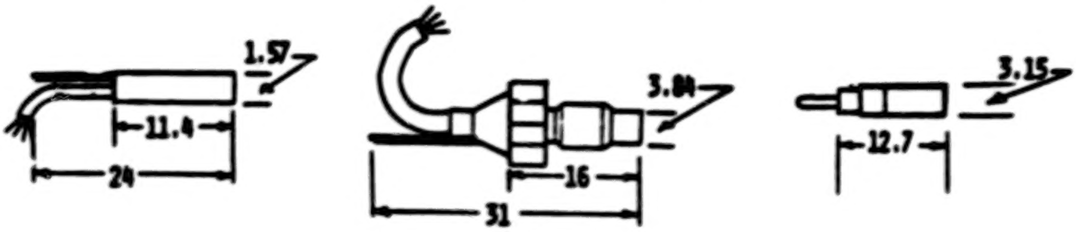


0.3-M TCT TEST



BEST DOCUMENT AVAILABLE

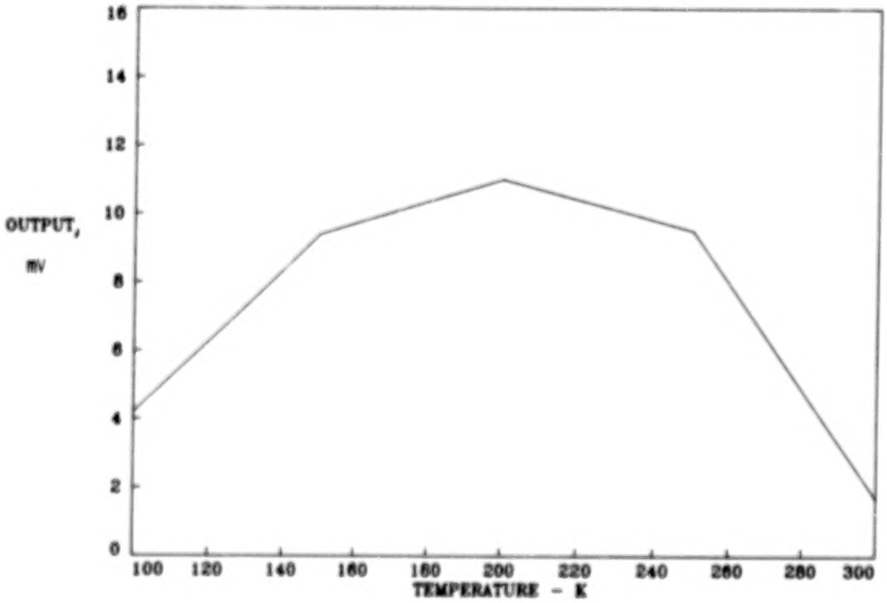
DYNAMIC PRESSURE TRANSDUCERS



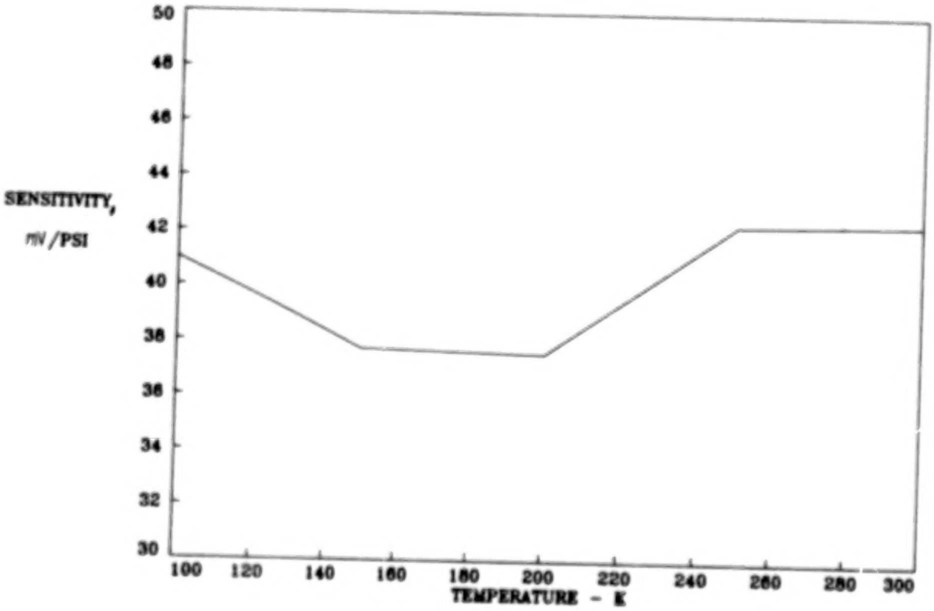
ALL DIMENSIONS IN MM

ERROR BAND	1% FULL RANGE		2% FULL RANGE
RANGE	10 PSI MIN	2 PSI MIN	100 PSI
OUTPUT	300 MV		2 V
THERMAL SENS	0.07%/K		0.06%/K
THERMAL ZERO	0.06% FS/K		
TEMP RANGE	100K INCREMENTS		90 TO 330K
MOUNTING	PROBLEM	THREADED	THREADED

THERMAL ZERO - ENDEVCO 8510-5



THERMAL SENSITIVITY - ENDEVCO 8510-5



ANGLE OF ATTACK SYSTEM

Tom D. Finley
NASA Langley Research Center
Hampton, Virginia

This presentation describes the work done toward making measurements of model pitch and roll attitude in the National Transonic Facility (NTF). The effort is divided between two approaches: (1) an inertial measurement that is an extrapolation of existing technology into a cryogenic environment, and (2) an optical technique developed by Boeing Aerospace Company, which is presently under contract to NASA to design, fabricate, and demonstrate a system capable of working in the NTF environment. This presentation describes the approaches, their promise and limitations, and the work done in each area up to the present. It also includes a summary of the status of each approach and plans for further work.

NTF MODEL ATTITUDE MEASUREMENT REQUIREMENTS

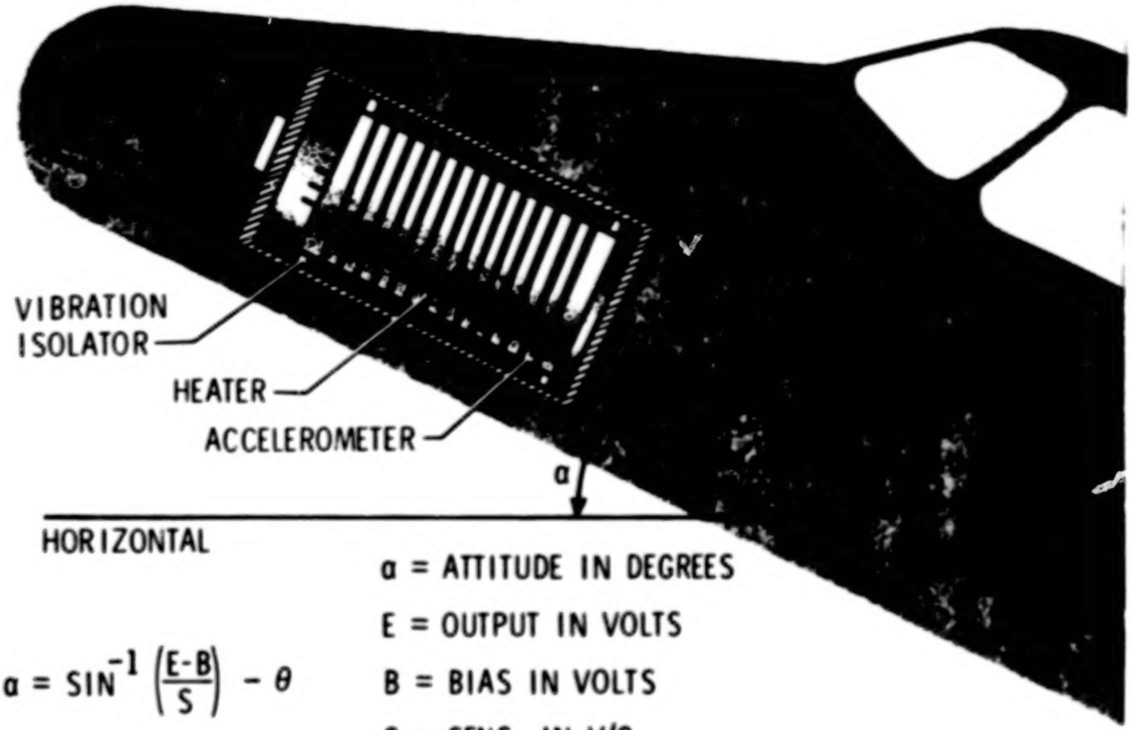
	PITCH	ROLL
RANGE	-13 + 30°	± 180°
ACCURACY	.01°	.03°
RESPONSE	1 sec	1 sec

BASIC APPROACHES

- INERTIAL SYSTEMS
  - OPERATION
  - ENVIRONMENTAL PACKAGE
  - MODEL REQUIREMENTS
- OPTICAL SYSTEMS
  - OPERATION
  - MODEL REQUIREMENTS

OTHER CONSIDERATIONS

MEASURING PITCH ATTITUDE WITH AN ACCELEROMETER


VIBRATION ISOLATOR
HEATER
ACCELEROMETER
α
HORIZONTAL

$$\alpha = \sin^{-1}\left(\frac{E-B}{S}\right) - \theta$$

α = ATTITUDE IN DEGREES

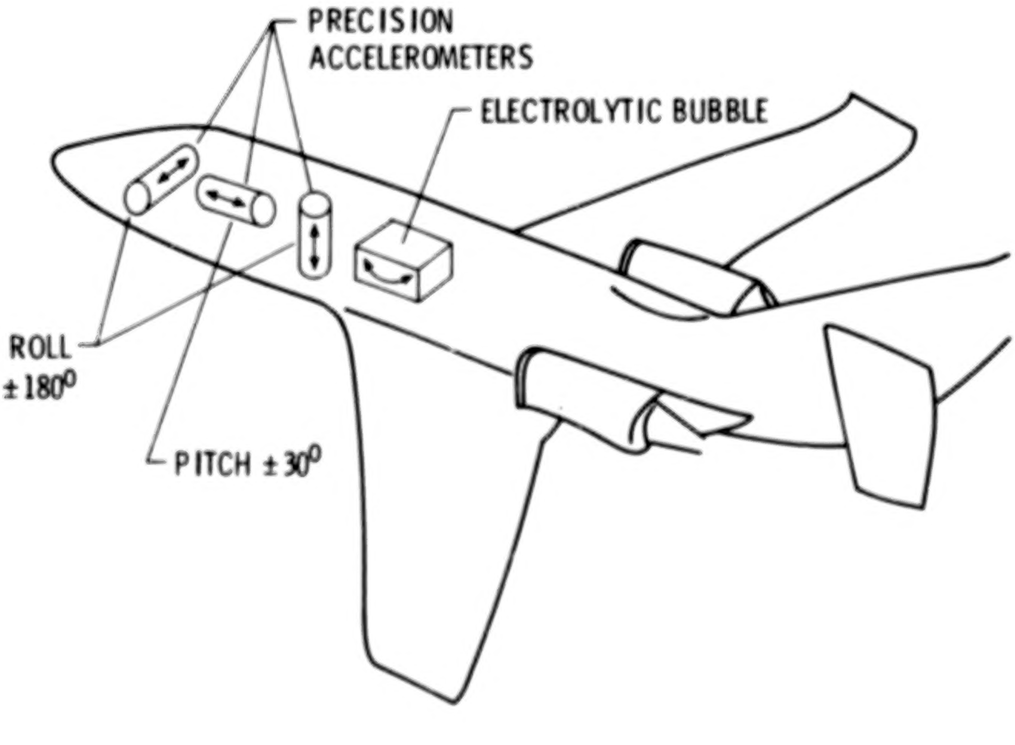
E = OUTPUT IN VOLTS

B = BIAS IN VOLTS

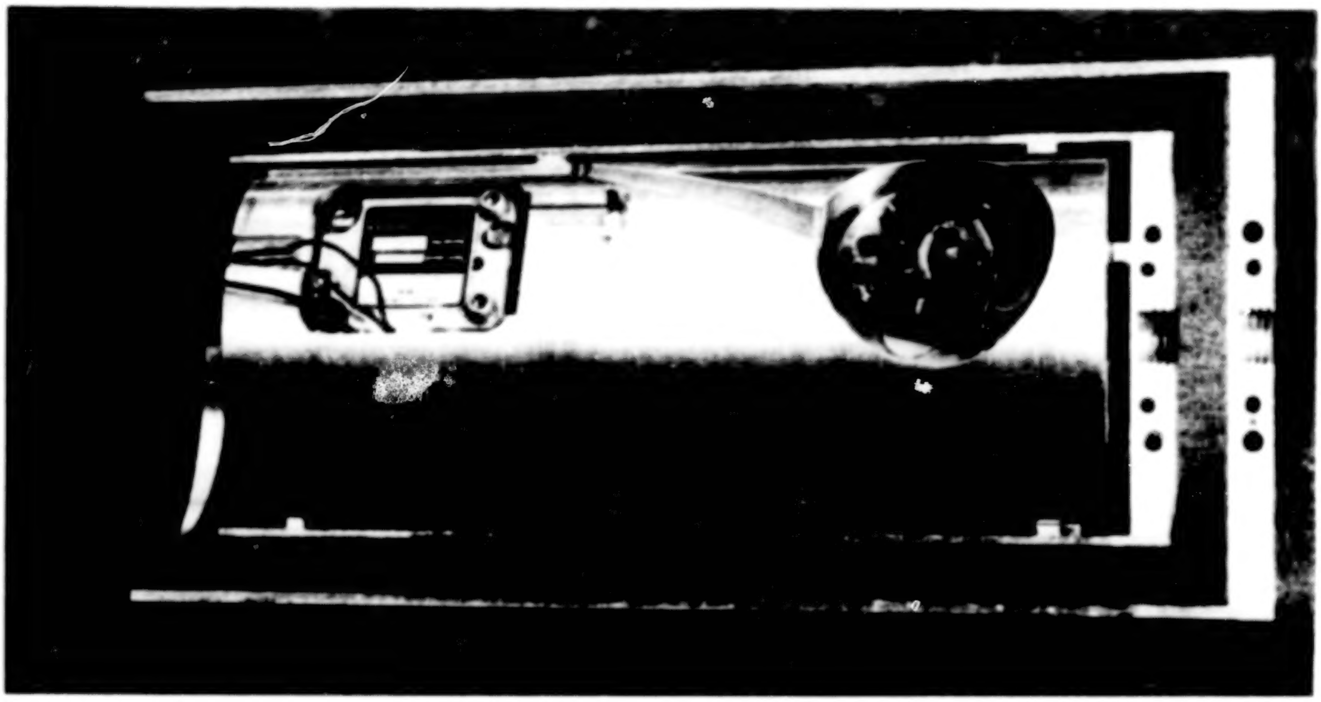
S = SENS. IN V/G

θ = MISALINEMENT IN DEGREES

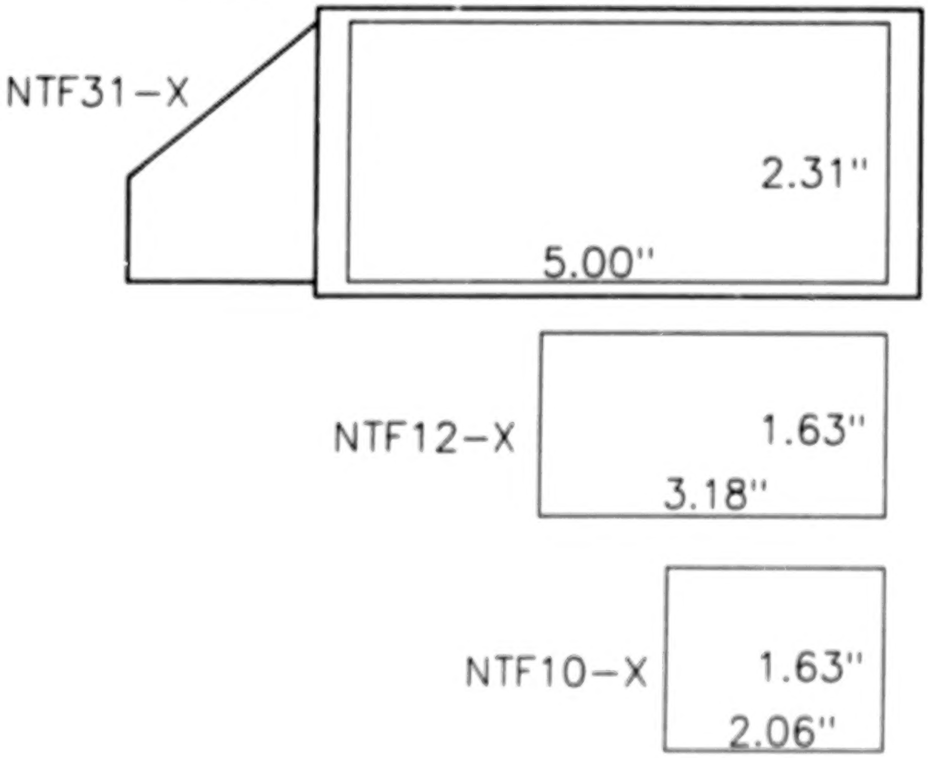
NTF MODEL ATTITUDE MEASUREMENT


PRECISION ACCELEROMETERS
ELECTROLYTIC BUBBLE
ROLL ±180°
PITCH ±30°

INSIDE VIEW OF NTF31-X INERTIAL PACKAGE



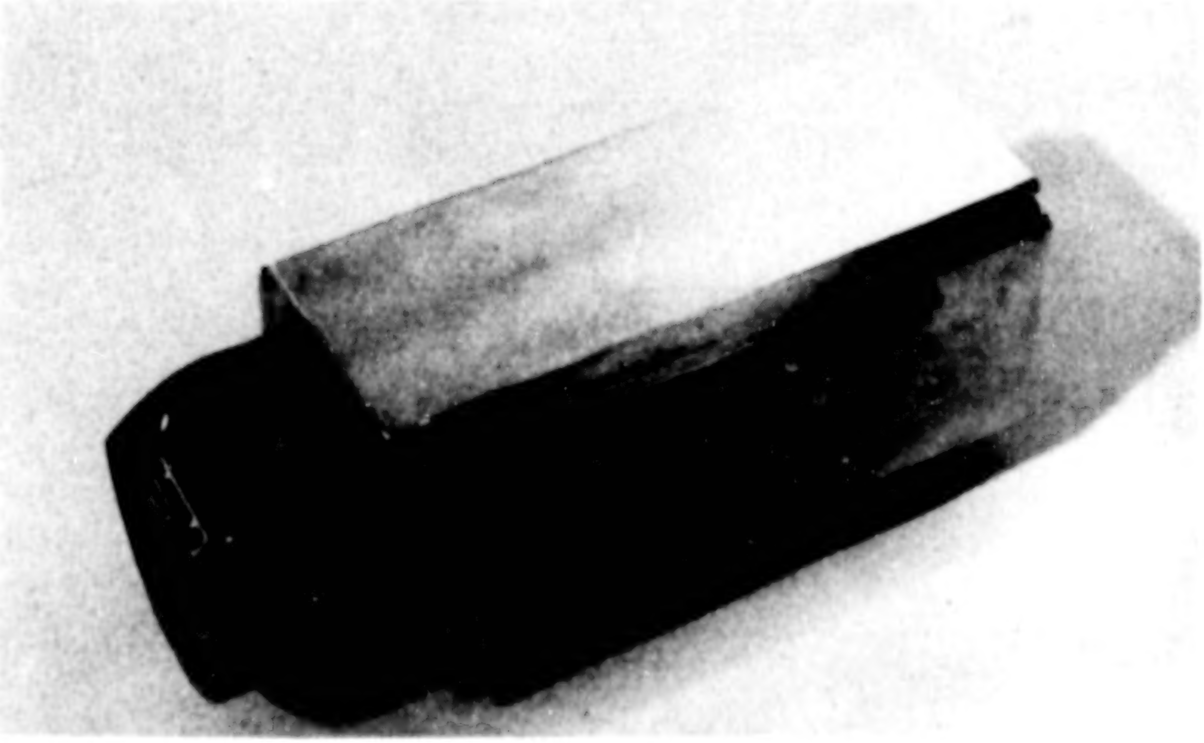
NTF INERTIAL PACKAGES


NTF31-X
2.31"
5.00"
NTF12-X
1.63"
3.18"
NTF10-X
1.63"
2.06"

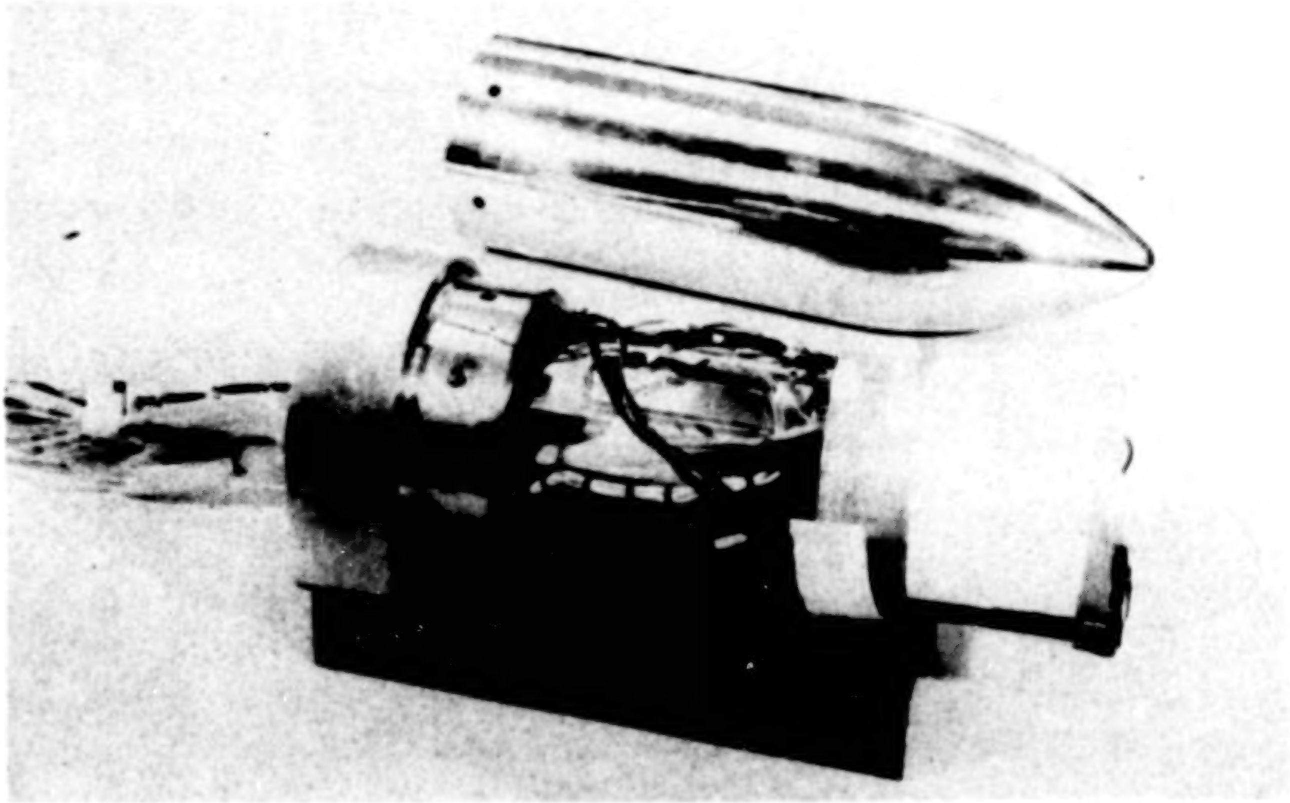
NTF PACKAGES

NTF31-X	•3 ACCELEROMETERS & 1 BUBBLE •MEASURES PITCH & ROLL •30 WIRES
NTF12-X	•1 ACCELEROMETER & 2 BUBBLES •MEASURES PITCH •15 WIRES
NTF10-X	•1 ACCELEROMETER •MEASURES PITCH •10 WIRES

NTF31-X INERTIAL PACKAGE

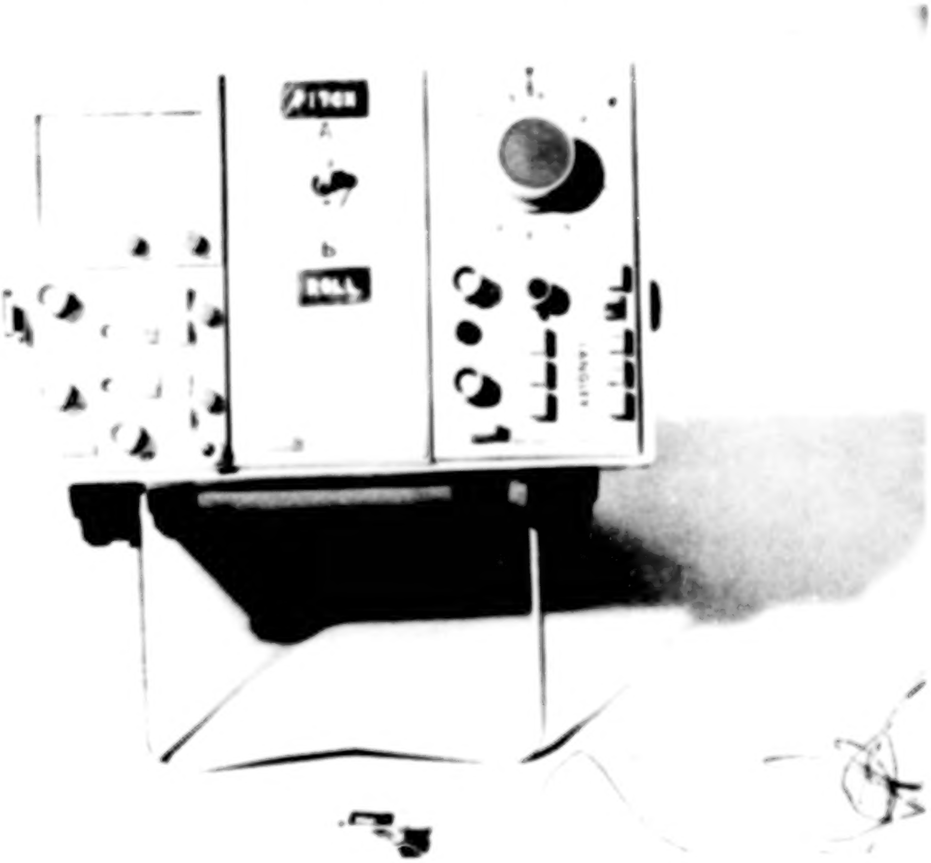


INSTRUMENTATION MOCKUP FOR PATHFINDER I MODEL

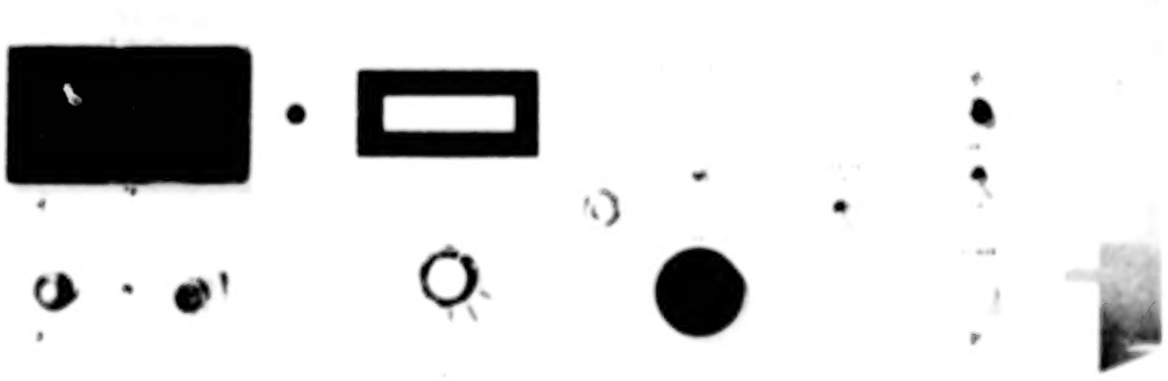


ACCELEROMETER POWER SUPPLY

OUTPUT MONITOR FOR ACCELEROMETER



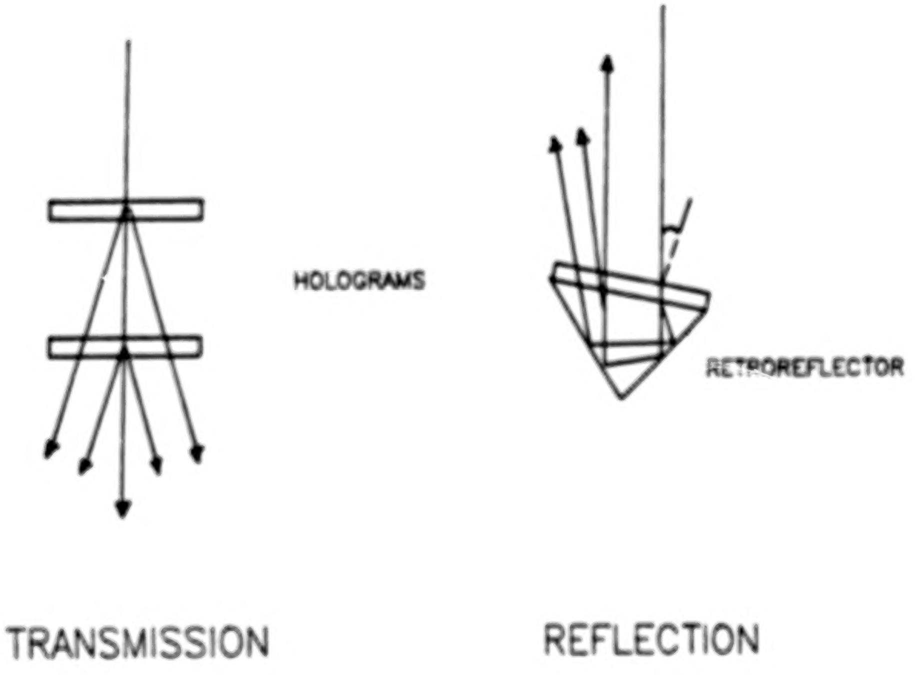
HEATER CONTROL BOX



LIMITATIONS OF ACCELEROMETERS

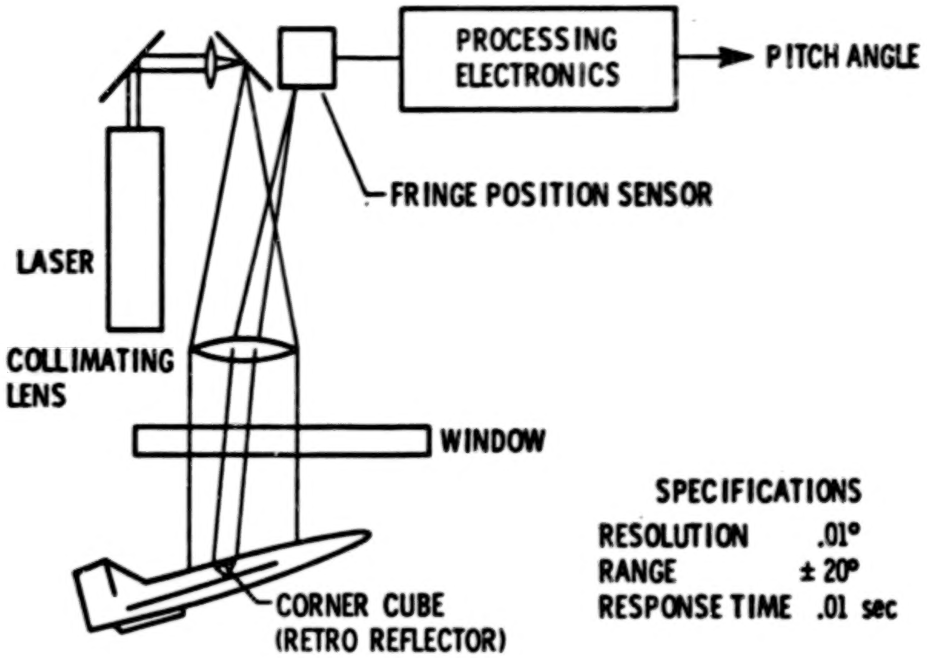
- DYNAMICS
- SLOW RESPONSE
- LABOR – INTENSIVE
- FRAGILE INSTRUMENTS
- LARGE PACKAGE (AND WIRES) IN MODEL
- MULTIPLE UNITS REQUIRED TO MEASURE 2 AXES

HOLOGRAPHIC ANGLE SENSOR


HOLOGRAMS
RETROREFLECTOR
TRANSMISSION
REFLECTION

BEST DOCUMENT AVAILABLE

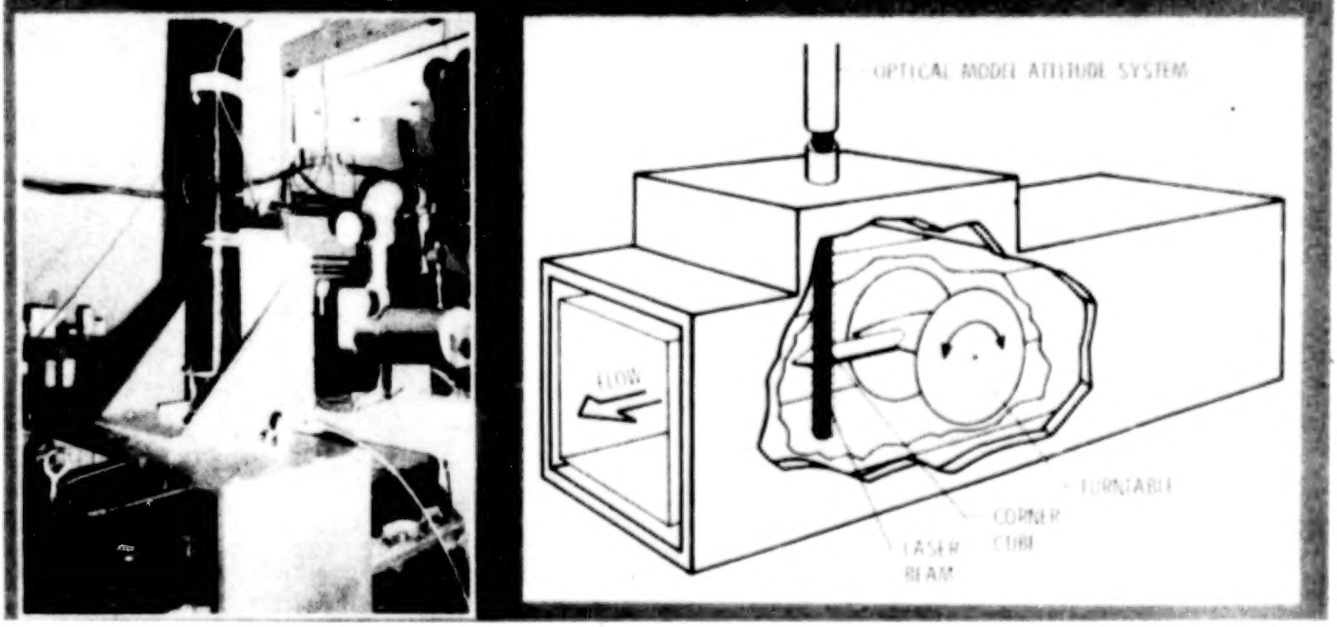
OPTICAL ANGLE SENSOR


PROCESSING ELECTRONICS
PITCH ANGLE
FRINGE POSITION SENSOR
LASER
COLLIMATING LENS
WINDOW
CORNER CUBE (RETRO REFLECTOR)

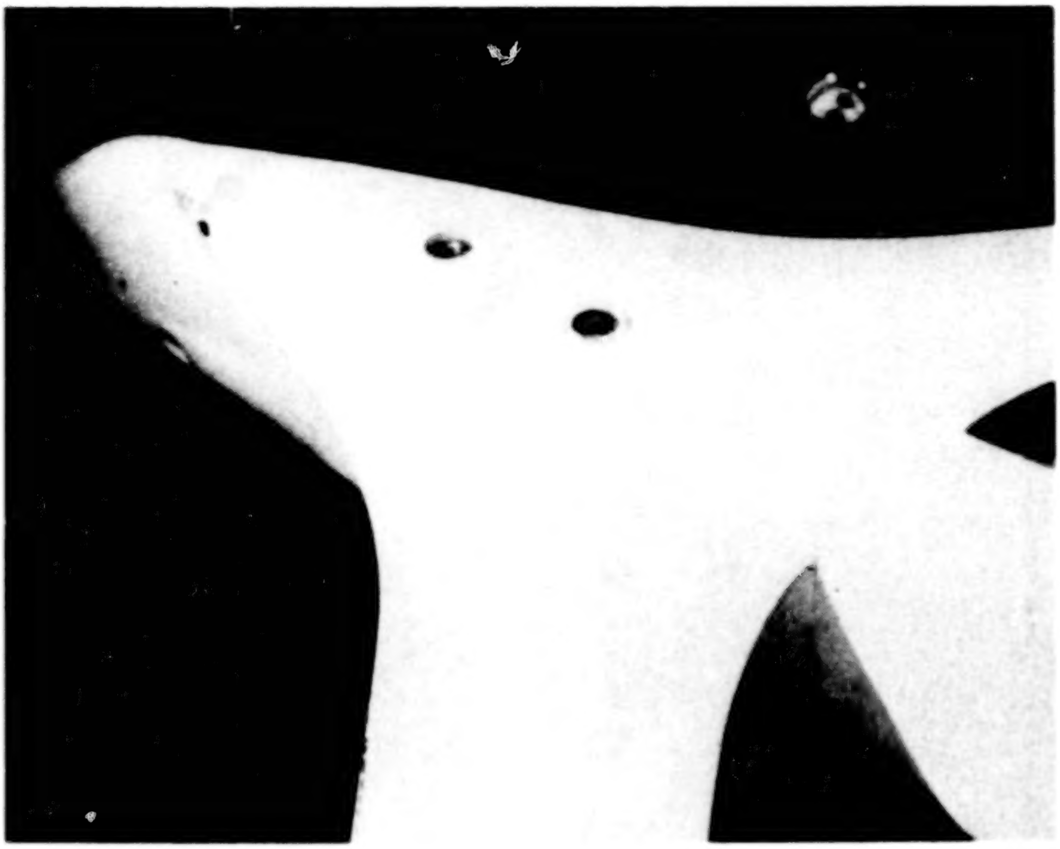
SPECIFICATIONS

RESOLUTION	.01°
RANGE	± 20°
RESPONSE TIME	.01 sec

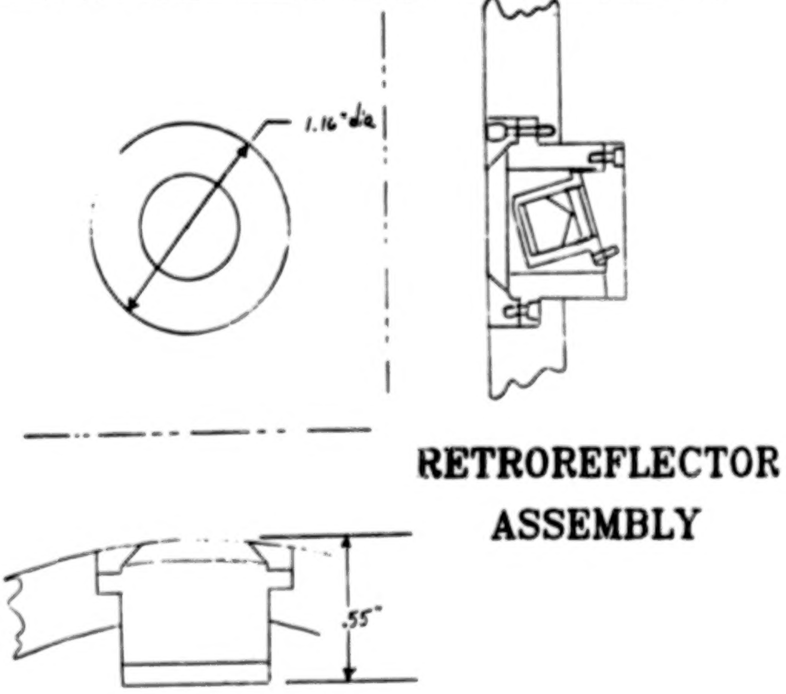
OPTICAL SYSTEM IN 0.3 METER TUNNEL


OPTICAL MODEL ATTITUDE SYSTEM
FLOW
TURNTABLE
CORNER CUBE
LASER BEAM

RETROREFLECTOR MOUNTED IN WIND TUNNEL MODEL



RETROREFLECTOR ASSEMBLY


1.16" dia
.55"
RETROREFLECTOR
ASSEMBLY

LEVELING SETUP FOR WIND TUNNEL MODEL

CONCLUSIONS

1. A RAPID, ACCURATE OPTICAL SYSTEM WILL BE AVAILABLE
2. INERTIAL PACKAGES WILL ALSO BE AVAILABLE
3. MODEL DESIGN AND FABRICATION WILL BE MORE DIFFICULT THAN WITH CONVENTIONAL MODELS

PANEL DISCUSSION SYNOPSIS

Panel Members

L. W. McKinney, NASA Langley Research Center, Hampton, VA
S. A. Griffin, General Dynamics Corp., San Diego, CA
E. J. Toscano, Grumman Aerospace Corp., Bethpage, NY
W. C. Whisler, Boeing Aircraft Corp., Seattle, WA

Although the need for high Reynolds number test capability has plagued aerodynamic researchers and aircraft developers for several decades, it was not until the late 1960's that this need was established as a national priority through formal statements by the Department of Defense, NASA, and the aircraft industry, with support from the various national scientific advisory committees. Thus, when construction and checkout of the National Transonic Facility (NTF) is completed, a major milestone will have been achieved in the 15 years of concentrated effort in the United States to obtain full-scale Reynolds number simulation on aircraft configurations in a ground-based test facility. The high-pressure cryogenic environment of the NTF requires the development of new test equipment, models, instrumentation, and, in some cases, test techniques for full utilization of its test capability. In keeping with the national charter of the NTF, and to obtain outside participation in our related activities, a series of workshops has been held over the past 7 years, of which this worshop is one. The topic of this panel discussion is "The Major Concerns and Problems of Designing and Fabricating Cryogenic Models and Some Potential Solutions."

In order to utilize the high Reynolds number capability of the NTF, the models must be designed not only for cryogenic temperatures, but also for relatively high dynamic pressure. (Dynamic pressures can range up to approximately 6900 psf, depending on the desired Reynolds number.) Also, to fully utilize this high Reynolds number capability, some models and model-support systems may have to be tested at working stress safety factors lower than those conventionally accepted. In order to safely accept lower factors, detailed stress, fatigue, fracture mechanics, flutter, and divergence analyses will be required, along with close quality assurance inspection of the model during all phases of fabrication. It is recognized that design and fabrication of models that require the added analyses and quality inspections will be somewhat more expensive than for "conventional" models designed for high-pressure wind tunnels. In addition, the requested fabrication tolerances and surface finishes, as well as the more difficult-to-machine materials used, will add to the model fabrication costs as compared to the costs for "conventional" models. However, as experience is gained by the researchers, model designers, and model builders, costs for the NTF models are expected to decrease substantially. It should be noted that fair comparisons between NTF model costs and "conventional" model costs are difficult, and care should be taken in making such comparisons because of the many different factors involved.

Although there are special problems associated with designing and fabricating models for the NTF, from all experience gained thus far, no "show stoppers" have appeared, and thus all problems have proven to be workable. For instance, the list of materials that are acceptable for cryogenic testing is rather limited at the present time, and the cryogenically acceptable steels on this list are generally more difficult to work with than "conventional" model steels. However, model builders have learned how to work with these materials and are now routinely fabricating models using cryogenically acceptable materials. It should be noted that not all cryogenically acceptable metallic alloys are noncorrosive, and special handling of some models will be required to prevent corrosion. It should be emphasized that all NTF users maintain frequent contact with NASA Langley personnel to insure that the most recent information is brought to bear on the solutions of any model design, analysis, or fabrication problems.

Work is ongoing not only by NASA but also by airframe companies to obtain acceptable cryogenic model filler materials. Three distinct needs can be identified as regards filler materials: (1) filler materials for areas of the model where removal of the material should not be required for the life of the model; (2) filler materials for areas of the model where the material needs to be removed only occasionally (e.g., once per test); and (3) filler materials for areas of the model where frequent removal and reapplication are required. At this point in time, the most difficult problem appears to be fillers for areas where frequent removal is required, since for this application quick curing times are required and the filler must be easily removable.

Proof-of-concept models and tests may prove to be well worth the investment, since changes to the model after fabrication is complete or nearly complete can be very expensive, if not impossible. Although proof-of-concept models and tests may not be fully conclusive, the tests can certainly point out weaknesses in a design or give confidence in a particular design.

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16. Abstract

The Cryogenic Wind Tunnel Models Workshop was held May 5-9, 1982, at NASA Langley Research Center. The principal motivating factor for the workshop was the construction and approaching commissioning of the National Transonic Facility (NTF) at Langley. Since the NTF can achieve significantly higher Reynolds numbers at transonic speeds than other wind tunnels in the world, and will therefore occupy a unique position among ground test facilities, every effort is being made to ensure that model design and fabrication technology exists to allow researchers to take advantage of this high Reynolds number capability. Since a great deal of experience in designing and fabricating cryogenic wind tunnel models does not exist, and since the experience that does exist is scattered over a number of organizations, there is a need to bring existing experience in these areas together and share it among all interested parties. As a result, this workshop included representatives from government, the airframe industry, and universities.

17. Key Words (Suggested by Author(s))

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Model fabrication
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Model materials

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